BRITISH WELDING JOURNAL

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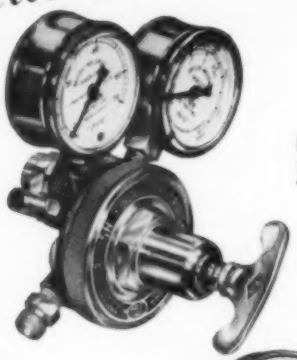

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Inside front cover

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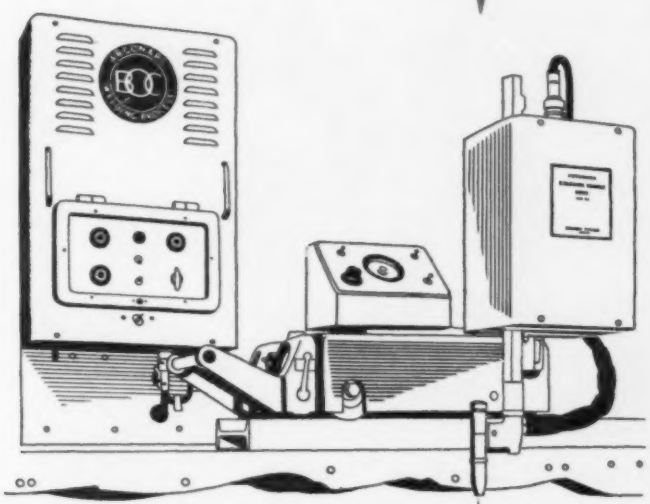

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The Self-propelled Mobile Mounting can be manoeuvred about the shop floor, enabling large components to be inspected without disturbing the flow of production. (Photo by courtesy of W. J. Fraser & Co. Ltd., Chemical Engineers).

Some tubehead mountings for the 250 kV Constant Potential X-ray Generator

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110 kVp *(Right)* The complete equipment on a mobile mounting. *(below)* A fluoroscopic cabinet which also provides facilities for radiography.

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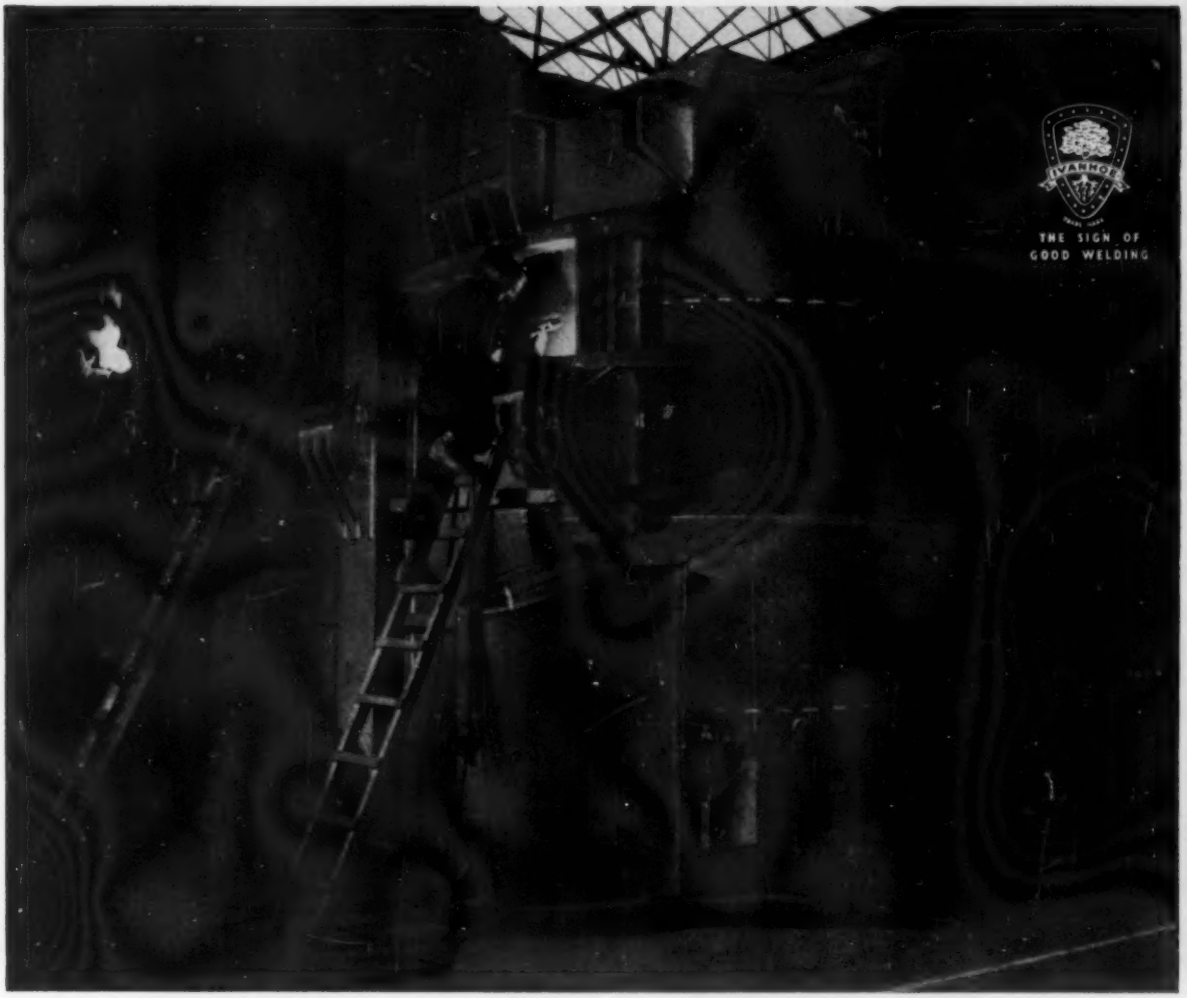

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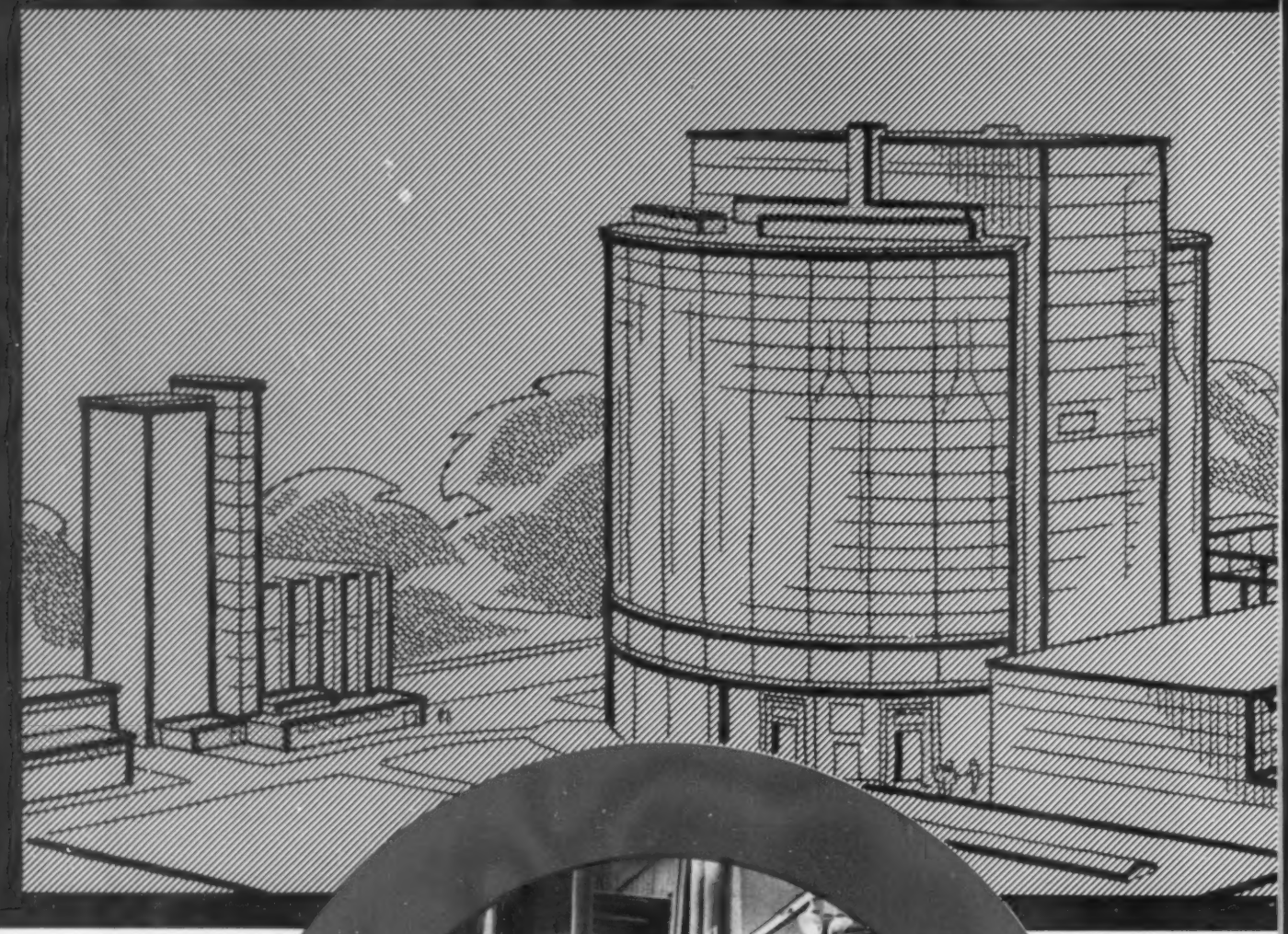
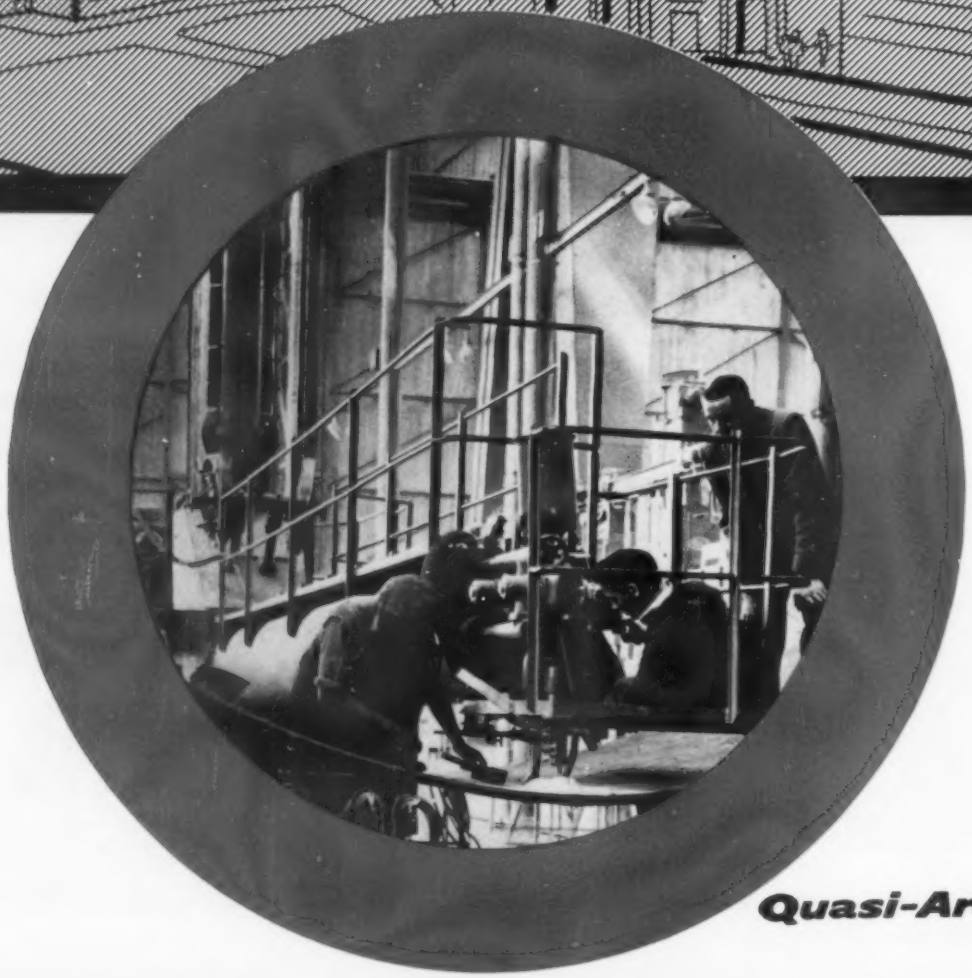
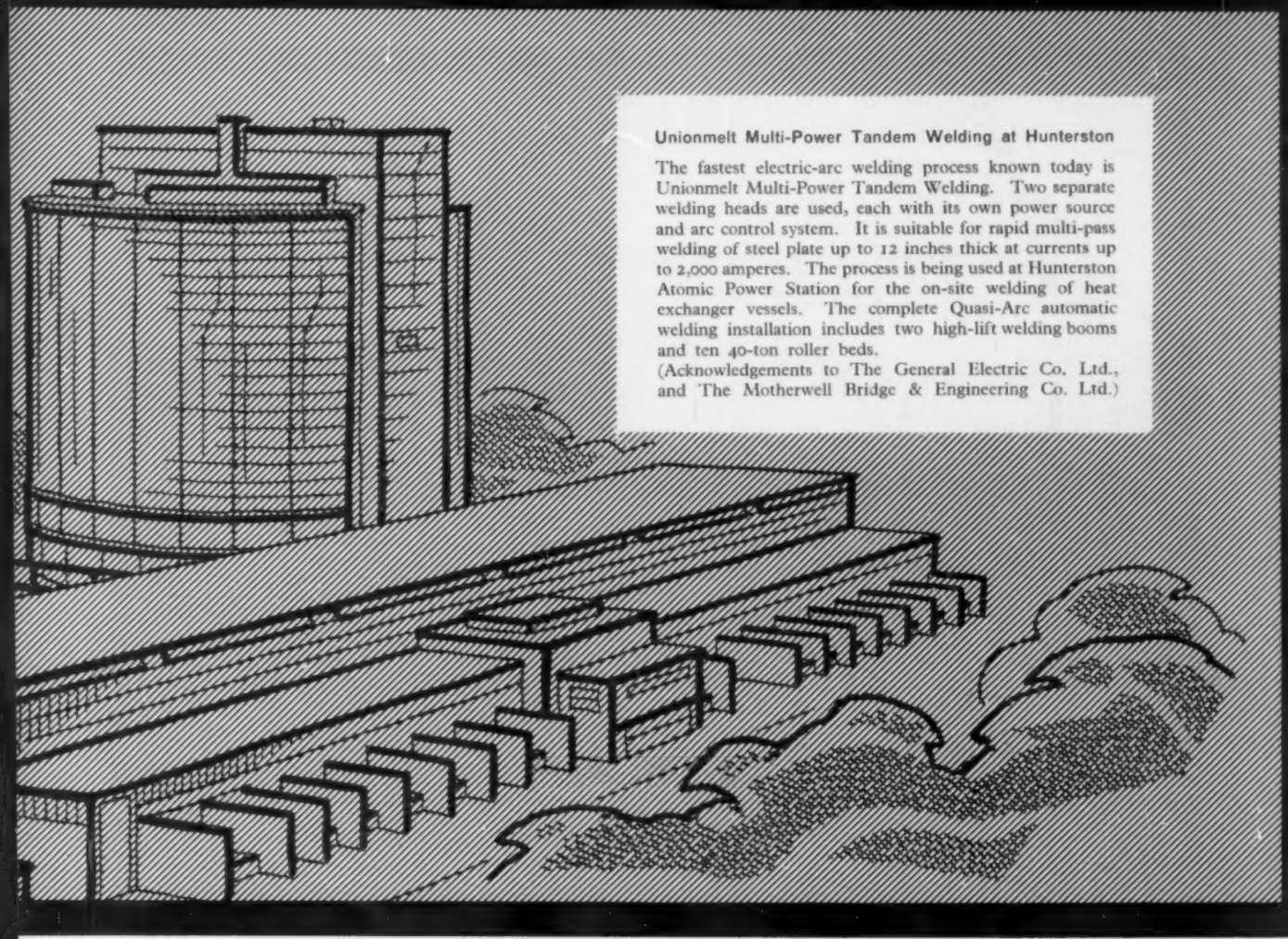




Quasi-Arc



Unionmelt Multi-Power Tandem Welding at Hunterston

The fastest electric-arc welding process known today is Unionmelt Multi-Power Tandem Welding. Two separate welding heads are used, each with its own power source and arc control system. It is suitable for rapid multi-pass welding of steel plate up to 12 inches thick at currents up to 2,000 amperes. The process is being used at Hunterston Atomic Power Station for the on-site welding of heat exchanger vessels. The complete Quasi-Arc automatic welding installation includes two high-lift welding booms and ten 40-ton roller beds.

(Acknowledgements to The General Electric Co. Ltd., and The Motherwell Bridge & Engineering Co. Ltd.)

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- wide range of welding heads—stationary and self-propelled—for a variety of duties.
- wide range of wires and powders available for various applications.
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The new Unionmelt powders now available have increased tolerance to steel plate conditions and are especially suitable for the welding of British-grade steels in this country.

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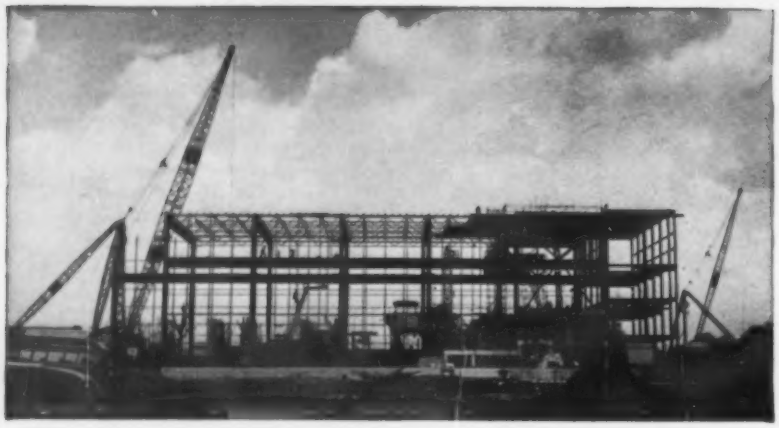

The buildings which comprise the new High Altitude Test Facility of this world-famous company, are of all-welded rigid frame construction. The total weight of steel involved is approximately 1,200 tons.

Consulting Engineers: McLellan & Partners in Association with Merz & McLellan.

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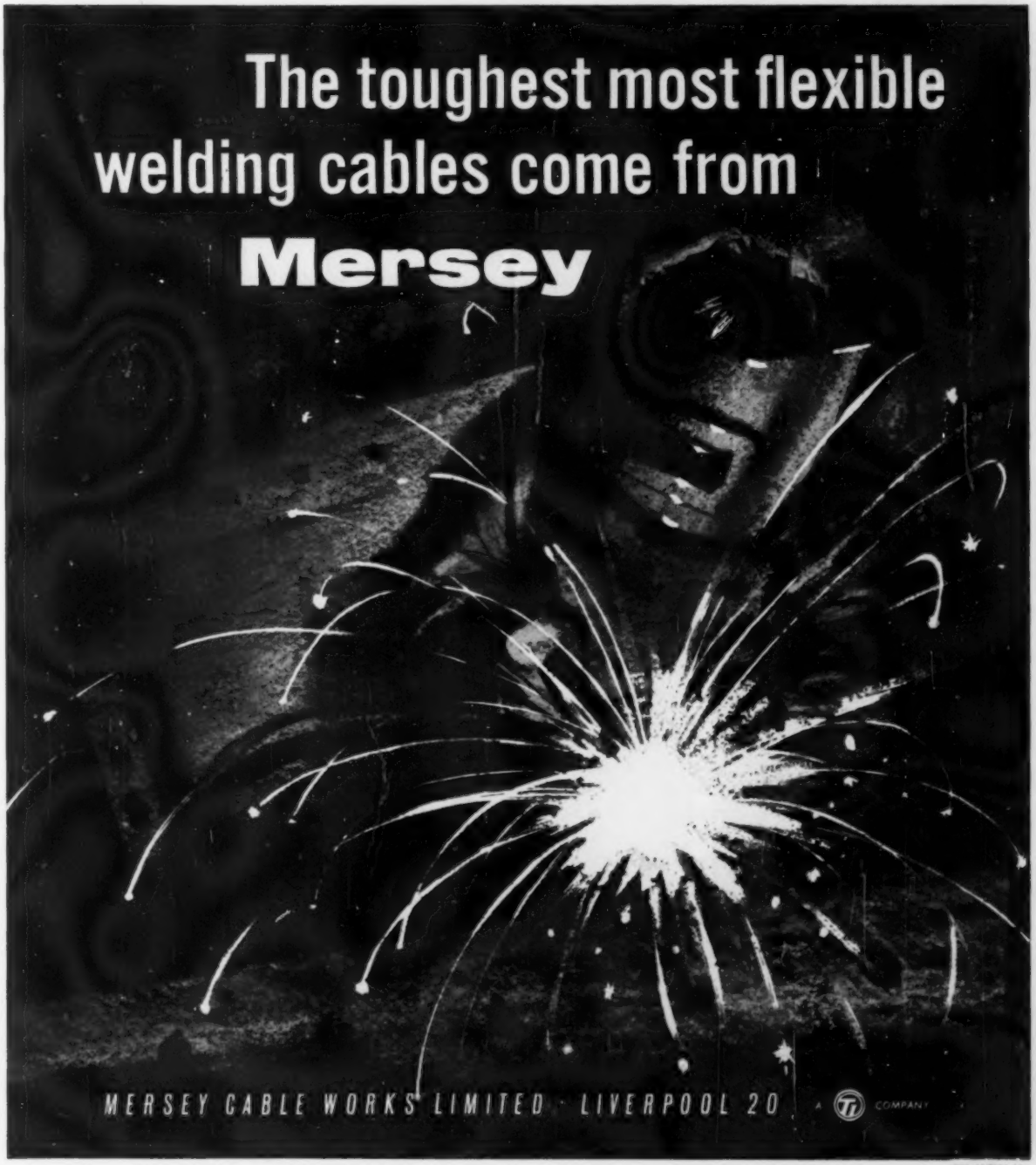
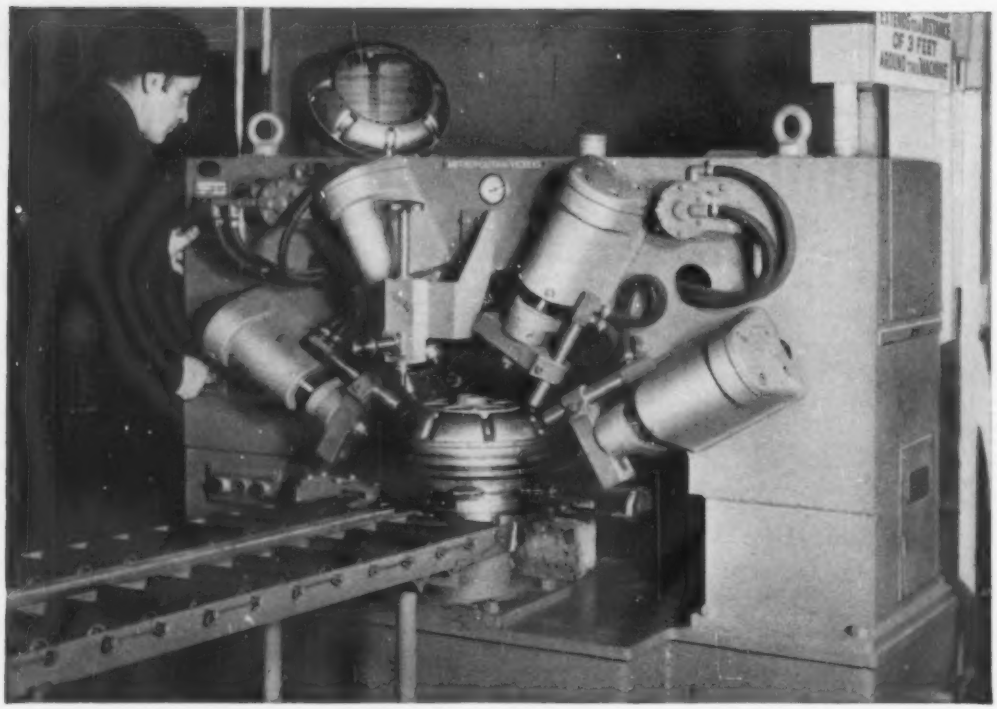


Metrovick Welding Equipment for Modern Engineering



Borg-Warner automatic transmission used on British and Continental cars is now produced entirely in this country. The fabrication of the hydraulic torque converter is an achievement which depended largely on solving a number of welding problems. Distortion had to be avoided because of the close dimensional tolerances required in many components and only a small departure from true balance is permissible with the high rotary speeds employed in the converters. In addition, the economics of present-day production necessitated fast, automatic welding techniques. All of these exacting and important welding requirements have been met by the use of several different types of Metrovick automatic submerged arc and resistance welding equipments, including a number of machines specially designed for the job.

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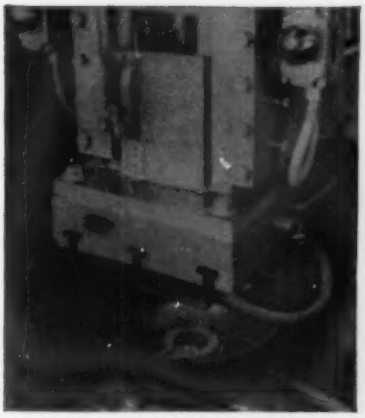
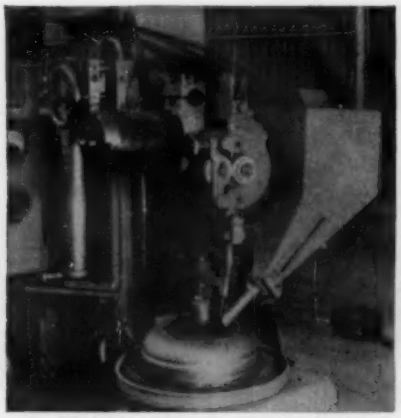
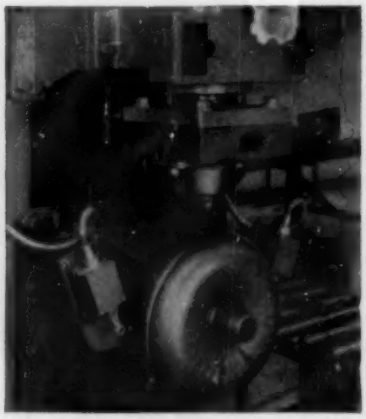


1. After the hub of the impeller has been pressed into its shell, the hub plate is welded inside the shell using a Metrovick 600 kVA projection welder.



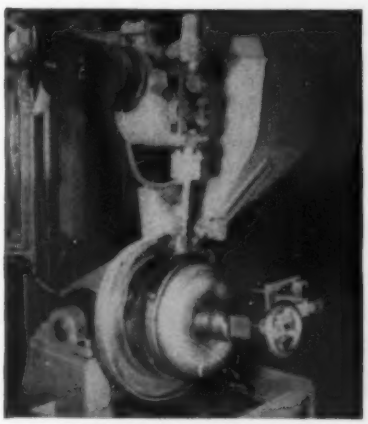
2. For welding the hub to the impeller shell a Metrovick submerged arc unit is used. An essential feature of this machine is the electronic control of the arc.



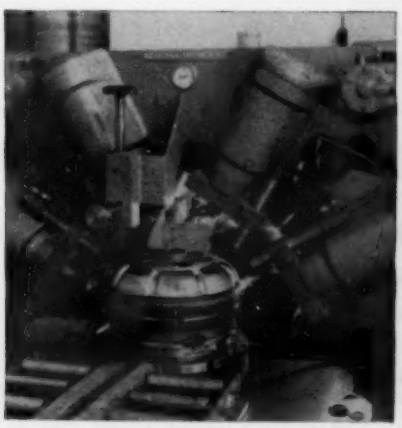
3. After vanes have been inserted, a filler adapter drain plug is welded into the impeller shell. A counterbalance weight is welded on the diametrically opposite side. This is carried out on a Metrovick 150 kVA air-operated projection welder, automatically setting the weld time for each operation.

Fabricating the BORG-WARNER HYDRAULIC TORQUE CONVERTER

4. The turbine assembly must be balanced to within 0.1 oz.-in. Balance is corrected by spot welding strip metal on to the vanes using a Metrovick 50 kVA portable machine.

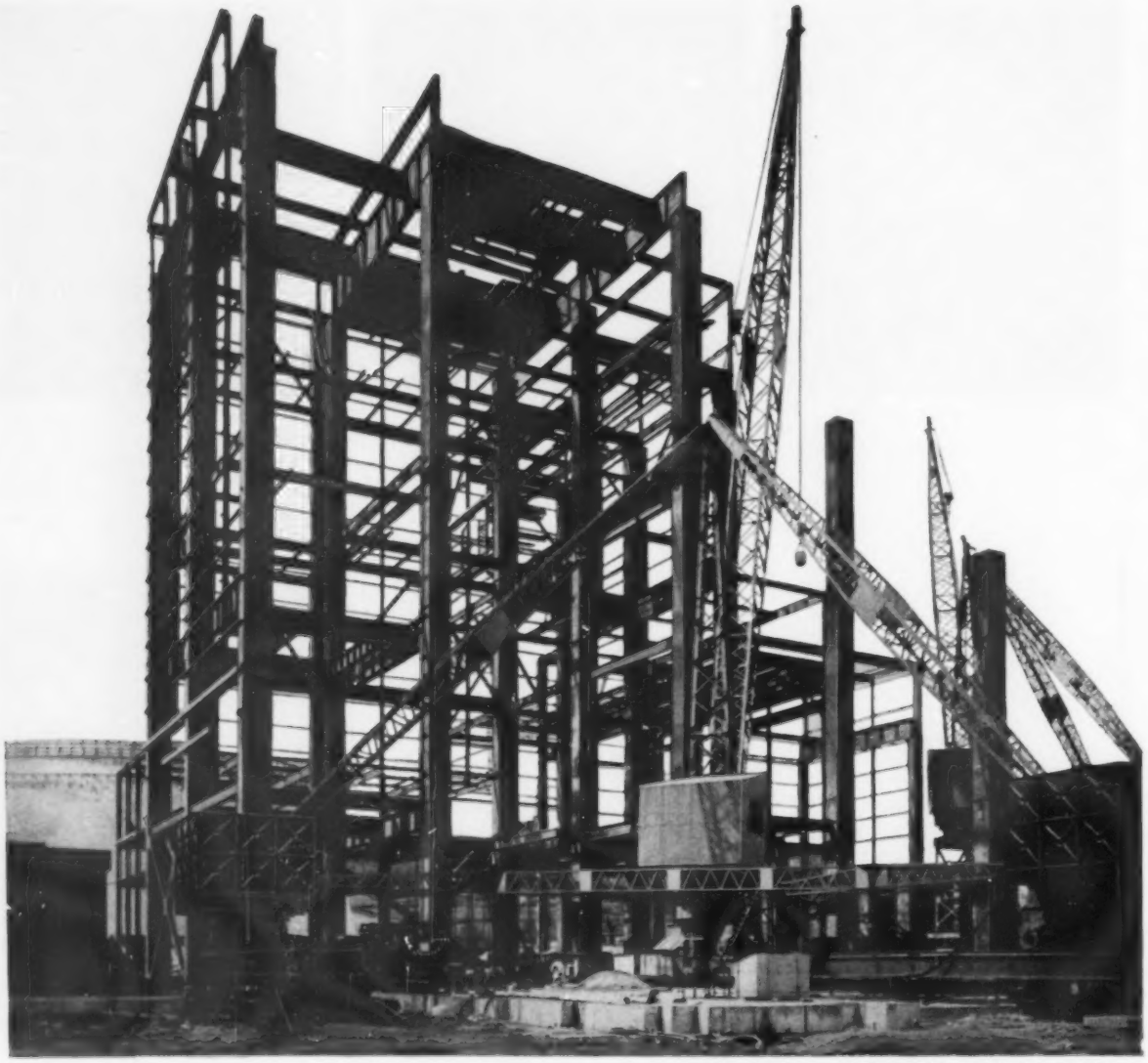


5. The completed clutch and flywheel assembly and the converter assembly are fitted together and then welded with a Metrovick submerged arc machine. This was specially designed for circumferential welds on Borg-Warner converter casings.



6. After testing the assembly for leaks a Metrovick Archway Type multi-spot unit is used to attach the blower. Sixteen spot welds are made with four air-operated heads. Control is by thyratron timer and ignitron contactor.

7. In the final balancing of the complete assembly this Metrovick 75 kVA portable spot welder is used for welding weights to the outer casing. The air-operated welding gun is mounted on a pivoting arm, balanced for ease of manipulation.



Consulting Engineers: Sir Bruce White, Wolfe Barry & Partners

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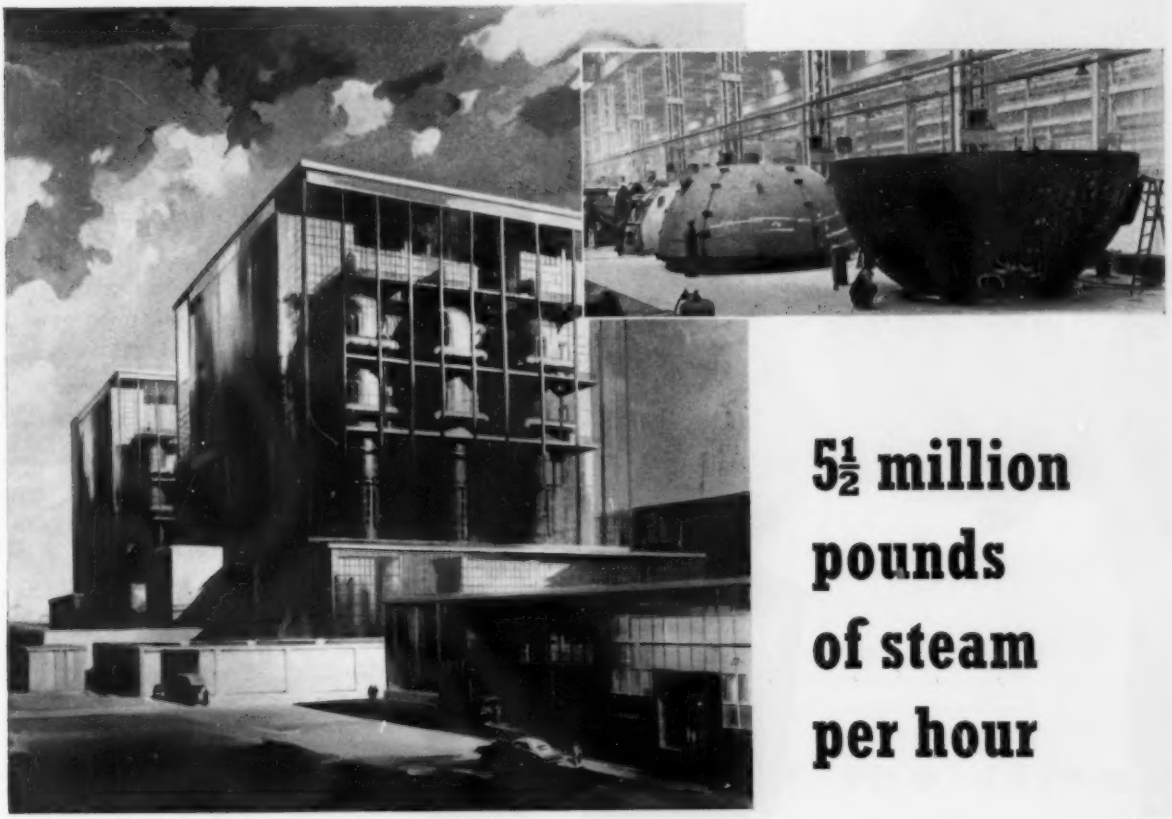

Illustrations by courtesy of Babcock & Wilcox Ltd.

5½ million pounds of steam per hour

The world's first 500MW atomic power station is being built by the English Electric, Babcock & Wilcox, Taylor Woodrow Atomic Power Group at Hinkley Point, in Somerset.

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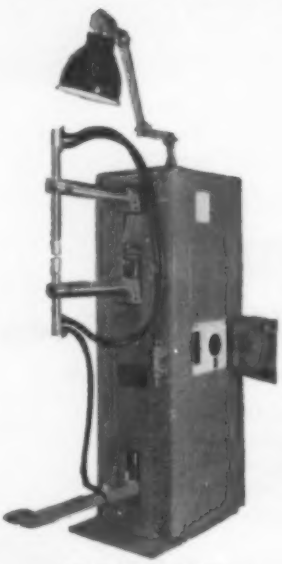

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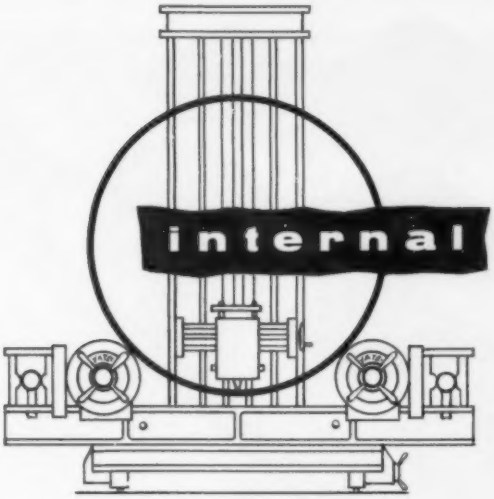

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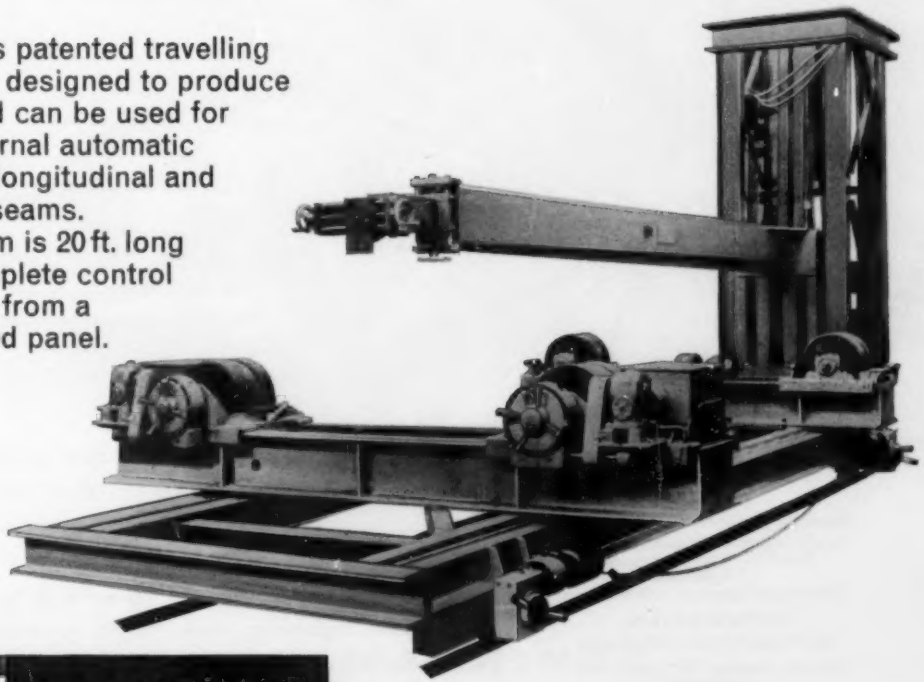

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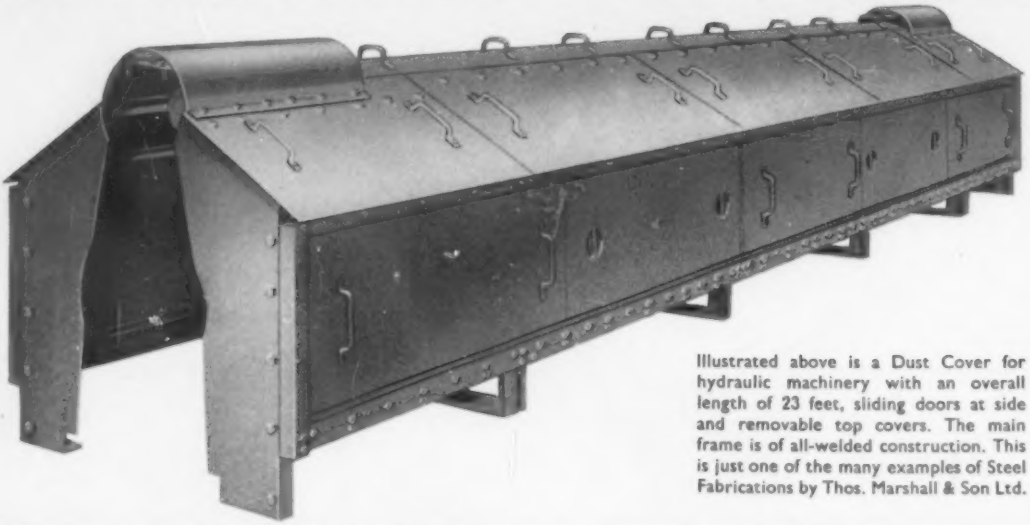

Illustrated above is a Dust Cover for hydraulic machinery with an overall length of 23 feet, sliding doors at side and removable top covers. The main frame is of all-welded construction. This is just one of the many examples of Steel Fabrications by Thos. Marshall & Son Ltd.

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★ SAFE LOW VOLTAGE ★ PORTABLE

Illustration shows typical set-up being prepared for heat treatment and welding

(photo by courtesy of Foster Wheeler Ltd.)

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Mk. 1a. 30" high by 25" wide and 28" long. This machine is mounted on castors and is both compact and mobile.
We also manufacture and distribute a wide range of Argon Arc Welding Torches, B.G.T. cutting and welding equipment and accessories. These, together with a daily delivery of Argon, Pyrogas etc., and a rapid equipment maintenance service are available at all our branches—Birmingham, Glasgow, Lymington, Manchester, Sheffield, Sunderland, Thornaby-on-Tees.

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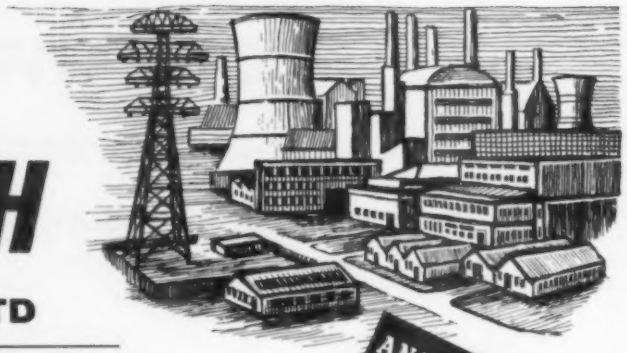

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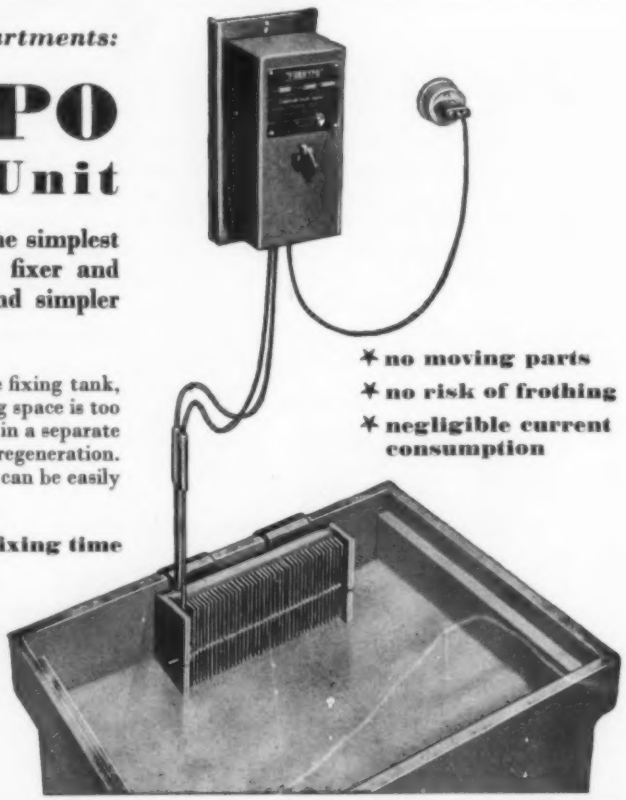

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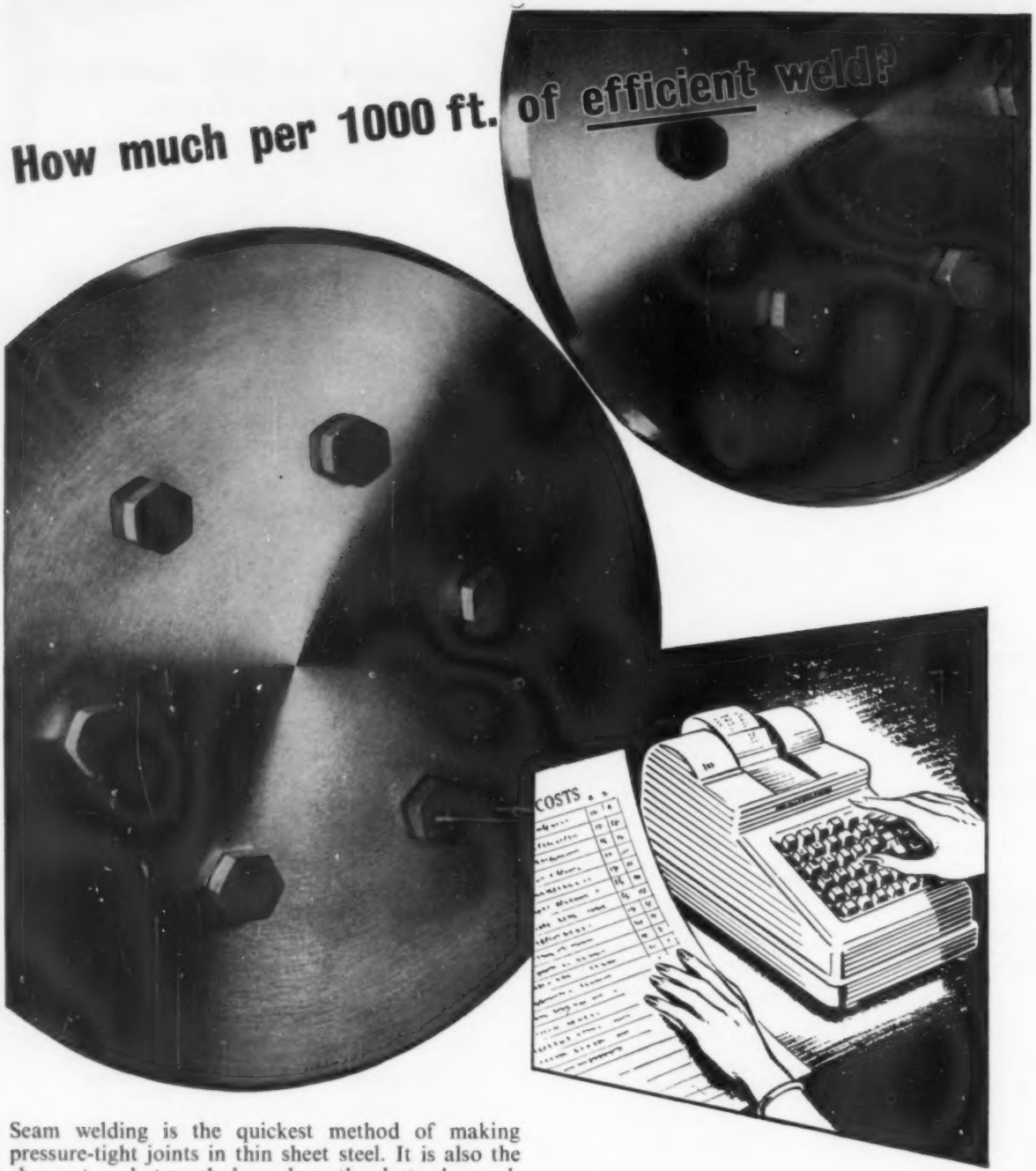

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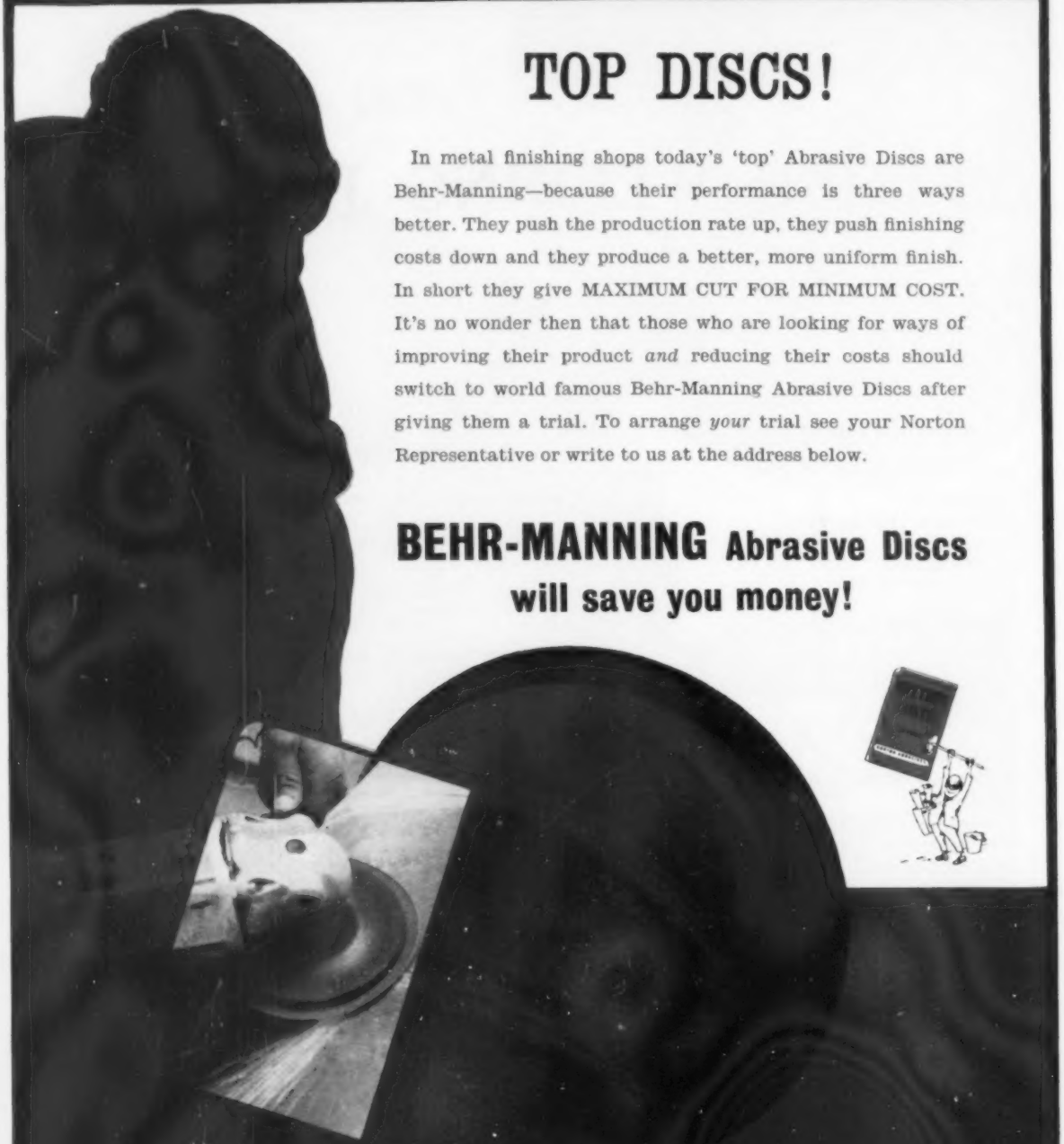

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PRESSURE WELDING CONFERENCE

Pressure Welding of Metals

A Conference on this subject was organized by the Department of Industrial Metallurgy at the University of Birmingham, on 19th June 1958, under the Chairmanship of Professor E. C. Rollason. The papers presented at the Conference were: (1) "Opening Address" and "Introductory Survey" by Professor E. C. Rollason; (2) "Industrial Practice in Cold Pressure Welding", by J. A. Donelan (Research Laboratories, General Electric Company); (3) "Pressure Welding by Rolling", by L. R. Vaidyanath, M. G. Nicholas and D. R. Milner (Department of Industrial Metallurgy, Birmingham University); (4) "Pressure Welding by Relative Movement Between Surfaces", by Dr. E. Holmes (Department of Metallurgy, Nottingham University).

INTRODUCTORY SURVEY

By E. C. Rollason, M.SC., PH.D., F.I.M., M.INST.W.

To supplement the academic work now being undertaken in the Department of Industrial Metallurgy at Birmingham University, occasional conferences[1] are organized to promote the exchange of information and ideas with other workers in the field and to bring together the 'know why' and 'know how' aspects of the work.

The subject of the second conference was Pressure Welding, a process which has developed largely empirically. As a result, the understanding of the phenomenon of pressure welding lags behind its practice and no satisfactory theory has been developed, although several hypotheses have been advanced as to the nature of the controlling parameter. The object of this brief introductory survey is to outline the origins and development of the practice of pressure welding and the progress that has been made towards establishing a theoretical model.

To the metallurgist there are three basic welding processes: fusion welding, brazing or soldering, and pressure welding. In the first two, intimate metallic contact is achieved by the use of molten metal with or without a flux. This molten metal serves two vital functions:

(i) It eliminates the need for smooth faying surfaces to secure intimate metallic contact, because molten metal accommodates itself to the contour of the metal being joined

(ii) The molten metal, with the help of fluxes or melted parent metal, removes non-metallic films from the surfaces being welded, thus assuring intimate metallic contact

In pressure welding the break-up of oxide films and intimate contact of surfaces have to be effected largely by pressure without the aid of molten metal.

Manuscript received 14th November 1958.

Professor Rollason is Head of the Department of Industrial Metallurgy at Birmingham University.

Historical Background

As early as 3000 B.C., in Egypt, iron was prepared by producing a metal sponge and hammering it to weld the particles together. From very early times, also, the idea of joining metals by pressure has been employed by the blacksmith in welding wrought iron; though this is a somewhat special case for the slag is molten at the welding temperature and is squeezed out from the joint.

The general realization that metals could be pressure welded came with the advent of resistance butt welding, invented by Professor Elihu Thomson in 1887. The process was accidentally discovered by reversing the current through an induction coil, which resulted in the ends of the primary coil welding together.[2] A description of the process appeared in the *Scientific American* of 26th November 1887.* Professor Thomson was very astute in realizing that resistance heating could be used to make joints, and such joints used to make money. As a result he formed a company which manufactured the machines, leased them out on a hire charge and also took 20–33% of the economy effected by the use of this technique.

In electric resistance welding, however, the non-uniform current distribution is liable to form a liquid phase locally, and it may be argued that this process is not strictly solid-phase welding. The first outstanding evidence of cold pressure welding was presented as early as 1724 by Rev. J. I. Desaguliers in a demonstration to the Royal Society. Figure 1, taken from the *Philosophical Transactions*, illustrates the experiment. Two lead balls, from which $\frac{3}{4}$ in. dia. segments had

*See reproduction on p. 186 of the *British Welding Journal*, 1955, vol. 2.

VI. *Some Experiments concerning the* Cohesion *of* Lead, *by the same.*

HAVING, on *Thursday* the 29th of *April* last, made mention of some Experiments, concerning the Cohesion of two Balls of Lead, applied together in a small Part of their Surface (so as to require a Weight far greater than what will overcome the Pressure of the Atmosphere, to separate them) made by *Mr. Triewall*, at *Newcastle*, and at *Edinburgh*; I made the following Experiment to the same Purpose, before the *Royal Society*.

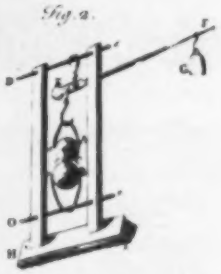
I took the Lesden Balls A and B (*Fig.* 1.) the first weighing one Pound, and the other two Pounds; and having from each of them cut off a Segment of about 1 Inch in Diameter, I press'd them together with my Hand, with a little Twist, to bring the flat Parts to touch as well as I cou'd. The Balls stuck so fast, that when the Hand H, by means of a String, sustain'd the upper Ball A, the lower one B (by reason of its Contact at C) was sustain'd, tho' loaded with the Scale S, and Weights E, which amounted to 56 Pounds. A little more Weight added separated them, and, upon viewing the touching Surfaces, it appear'd that they did not exceed a Circle of $\frac{1}{4}$ Inch Diameter; but this Surface can hardly be measur'd exactly, on account of its Irregularity. The Experiment was repeated several Times, and the Cohesion of the Balls was different every Time.

On *Thursday* the 6th of this Month, I made the Experiment another Way, at the Meeting of the Society, and just after their Rising, before several of the Members.

Philos. Transact. N° 389.

Fig. 1.

Fig. 2.



1— *Reproduction of Desaguliers' description of his cold welding experiments* (From *Phil. Trans. Roy. Soc.*, 1724, vol. 33, p. 345)

been cut, were pressed together with a twist and were found to be joined. The joint strength was measured on a steelyard and, although there was some scatter in the results, good bonds were produced with some as strong as that of solid metal. It is to be noted that both pressure and movement across the interface were used. In spite of this early demonstration of solid-phase welding the process was mainly limited to roll bonding of clad metals, which was developed from about 1935. The second world war accelerated further developments, especially in Germany where light alloy cooler elements for aircraft were pressure welded in Pantal. From 1945 the pioneers in Great Britain of the application to small components were the General Electric Company, which carried out a considerable amount of work on the development of suitable surface preparation techniques, dies and tools for giving satisfactory cold pressure welding. Now it is widely accepted that most metals can be pressure welded, if not at room temperature, then at higher temperatures.

An advantage of the process is that the joint possesses none of the weaknesses inherent in the cast structure associated with 'fusion' techniques, and in fact the forged structure is advantageous with metals such as beryllium and molybdenum. It is also the only metallic joining process which can be carried out at room temperature, and it is therefore particularly suitable for the 'canning' of delicate components such as detonators and transistors. Its main disadvantage results from the high plastic deformation and pressures required, but further research and suitable design work may indicate ways of minimizing these.

Types of joint and bond strength

Three common forms of joint, shown in Fig. 2, consist of small tool welds used instead of riveting processes; butt joints for joining rod, tubes, etc.; and roll-bonding used for the production of clad metals, or the manufacture of heat exchangers by blowing out an unwelded pattern of passages.[3]

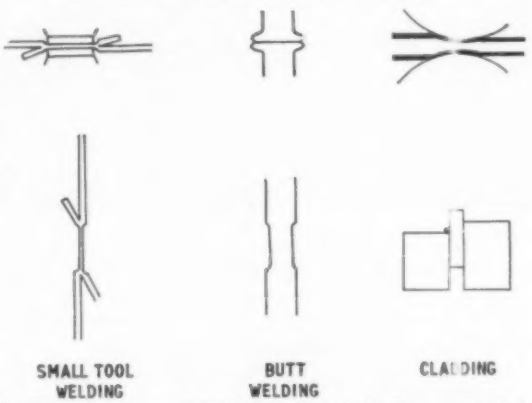
Two new developments, involving little deformation, are pressure welds on small angled tapered shapes such as turbine blade shanks, and the application of ultrasonic vibrations.[4] This latter process is claimed to involve less than 5% deformation and low static force, but it possibly produces localized heating at the junction faces.

The normal methods of measuring the bond strength of the three common forms of pressure welded joints shown in Fig. 2 are as follows:

(*a*) Small tool welds are tested by a tension-shear test, which gives a value between the tensile and shear strengths of the joint. The actual area of weld is not known and it is not always satisfactory to use the tool area; also at high deformation the joint becomes stronger than the parent metal

(*b*) Butt welds are most conveniently tested as tensile specimens, but the joint strength is probably not uniform across the interface

(*c*) Clad materials present a very difficult problem; a shear test is specified in A.S.T.M. standards, but it requires considerable preparation and is not widely used.



2—*Types of pressure welded joint and methods of measuring their bond strength*

As these tests were not entirely satisfactory in giving unambiguous results the Birmingham workers spent some time on the development of a new test which would be capable of giving results amenable to analysis.

Important Parameters and Theories of Pressure Welding

In the past, an empirical approach has been sufficient to establish suitable conditions for producing bonds of adequate strength. But with increased application of the process there have been many more papers dealing with fundamentals and establishing the important parameters, though the work has not yet led to a satisfactory model. Most workers have assumed that welding is controlled by one particular parameter and have usually investigated this to the exclusion of others.

Some of the less important factors affecting weldability are similarity of crystalline orientation of mating surfaces, elastic recovery, prestraining, and subsequent heat-treatment. The parameters with the greatest influence however are temperature, deformation, pressure, surface condition, and surface movement. These are briefly considered in the following section.

Temperature

At first it was thought that heating was essential to bonding, and even now some workers[5] regard temperature as being the overriding factor. This can be so, of course, at the extreme end of the range, *i.e.*, with light pressure.

The main effects of heating are:

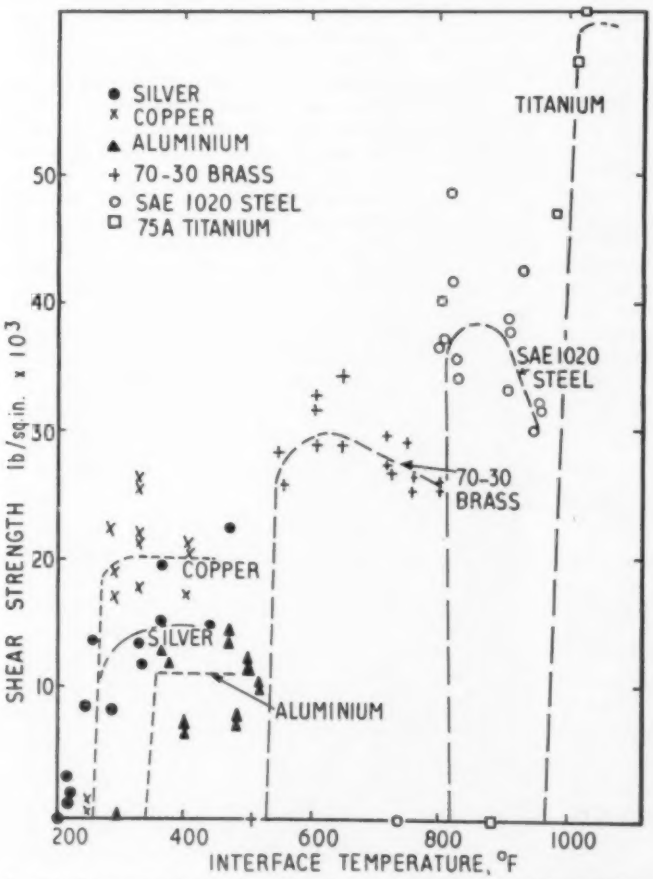
(*a*) It may increase the solution or cause melting of the oxide film, or evaporate the surface contaminants

(*b*) It increases atom mobility, *i.e.*, diffusion, and these atomic movements are particularly pronounced at allotropic transformations[6] and at recrystallization temperatures.[5] Parks, in his work on small tool welding, held the pieces in contact at a low pressure and with very little deformation and measured the temperature at which bonding commenced. These temperatures (Fig. 3), were closely related to the particular recrystallization temperature for the given material, which gave rise to the term 'recrystallization welding' for such temperature and pressure conditions

(*c*) It lowers the yield strength until it is zero at the recrystallization temperature. A low yield strength particularly allows plastic flow of surface asperities and increases the area of contact.

Deformation

With the advent of cold welding the emphasis was



3—*Interface temperature and resulting shear strength. The interface temperature corresponds to the recrystallization temperature* (Parks[5])

Table I

Relative cold weldability of materials

$$\text{Figure of merit} = \frac{\text{Final thickness of weld}}{\text{Twice the original thickness of a sheet}} \times 100$$

Material	*Figure of merit*
Super-pure aluminium	40
Commercially pure aluminium	about 30
DTD.346 (515)	29
BA.60A (35) (1¼% Mn)	20
Duralumin	20
Cadmium	16
Lead	16
Copper	14
Nickel	11
Zinc	8
Silver	6

Table II

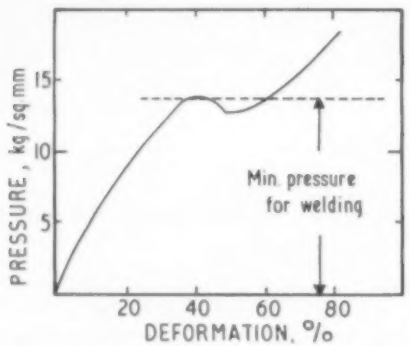
Minimum pressure for welding

Material	*Pressure, kg/sq.mm*
Tin	9
Aluminium (annealed)	16
Aluminium (hard)	20
Pantal	32
Copper	48
Armco iron	75
18/8 Stainless steel	200

to some extent removed from recrystallization and became focussed on the degree of deformation, which is correlated with weldability. For small tool welding, Sowter[7] used a 'figure of merit' to classify a number of metals, as shown in Table I, but many workers would not now agree with this order of weldability.

Pressure

Some workers regard pressure as being the most important parameter. Hofmann and Ruge[8] measured the pressure during small tool welding and found that there was a critical value at which the deformation increased rapidly (incidence of easy flow); they came to the conclusion that the easy flow was associated with the commencement of the formation of weld bridges. Thus a measure of the pressure necessary for the onset of easy flow was in effect a measure of weldability and they therefore classified their materials accordingly (Fig. 4 and Table II).



4—*Relation of 'easy flow' to welding pressure* (Hofmann & Ruge[8])

Table II places the emphasis on the metal flow occurring from pressure. These German workers have also referred to time as a variable and found that at constant pressure the deformation can be controlled by varying the time of pressure application. Other workers found little difference between slow or impactive loading.

Surface condition

Another factor which has often been put forward as being of prime importance is the state of the surfaces to be joined.

Metallic surfaces are usually rough and when two clean surfaces are pressed together contact will occur at a few asperities which deform and form junctions. In practice, metal surfaces are covered with thin oxide films which increase in thickness when the metal is heated, and some workers consider that the dispersion of the oxide is of paramount importance. Chief of these protagonists is Tylecote[9,10] who by analogy with work in the friction field concluded that the weldability of some metals is related to ease of rupturing the oxide layer, as shown by the ratio:

$$\frac{\text{Hardness of oxide film}}{\text{Hardness of metal}}$$

More extensive tests, however, revealed that the ratio was likely to be unimportant for most common metals and alloys in deciding weldability.

In addition to the oxide layer other surface contaminants may be present. Examples are grease, chemical compounds remaining after pickling, and adsorbed moisture; and these will inhibit welding, at least at room temperature. Mechanical removal (*e.g.*, scratch brushing) of the contaminant usually ensures the most satisfactory surface, but welding should be carried out immediately after the treatment.

Scratch brushing has also been shown to produce a work-hardened brittle layer on the surface,[11] and deformation breaks this layer into separate discontinuities.

Relative movement of surface

This is often an important factor and is discussed in Dr. Holmes' paper (p. 29).

Conclusions

When one considers this variety of parameters and the difficulty of devising a way of measuring the bond strength which can be related to the fundamental properties of the metal, and that for the welding of dissimilar metals the development of alloys, and in particular intermetallic compounds, complicates the interpretation of results, it is no small wonder that no comprehensive theory of pressure welding has yet been devised. The view taken by the Birmingham welding team is that all the factors and theories have a place, but sometimes in a modified form, and that the solution can be found only by making an initial simplification to provide a system that can be analyzed. This has been the guiding principle in their work.

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INDUSTRIAL PRACTICE IN COLD PRESSURE WELDING

By J. A. Donelan, A.M.INST.W.

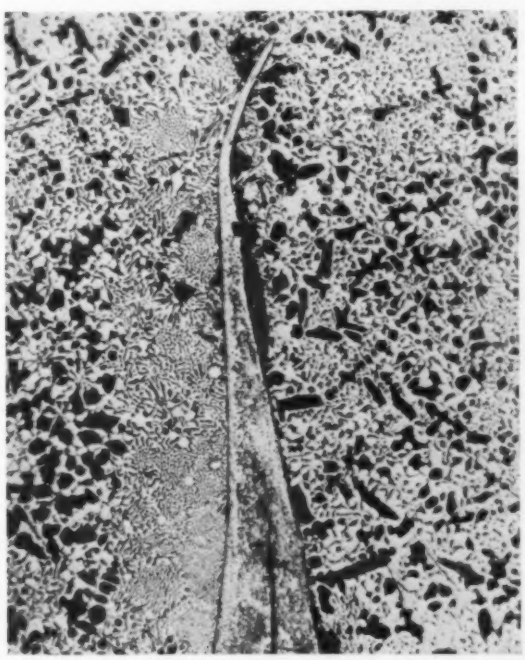
Cold pressure welding has been used as an industrial process for several years. The principles of cold welding, preparation of metal surfaces for welding, and the influence of die design on weld strength are described.

Applications of the process to the welding of aluminium and copper foil, sheet, wire, rod, and tubes for the electrical, electronic, and other industries are reviewed.

COLD WELDING is a method of joining similar or dissimilar ductile metals by bringing the surfaces to be joined into an intimate and expanding area of contact under pressure. Before welding, it is generally necessary to remove barrier films which would interfere with metal-to-metal contact. This may be partially achieved by chemical or mechanical means prior to the application of pressure, and partly or wholly by disruption of the surface during plastic flow.

The earliest industrial application of cold welding was the 'pinch-off' seal. This was a method of closing metal pumping tubes on thermionic valves, by squeezing the tube between cylindrical dies until it was severed; the opposite walls of the flattened tube were brought into intimate contact, and the surface films present were disrupted by the stretching of the metal during plastic deformation. Figure 1 shows a transverse section, parallel to the axis of the tube, through such a seal in aluminium.

A study of this process, and observations that ductile metals could be made to weld by the shearing action of cutting tools, indicated that the principles of cold welding could be extended to a wide field of metal joining applications, for both lap and butt welds.



1—*Transverse section through 'pinch-off' seal in aluminium tube* ×100

In cold pressure lap welding, the two superposed metal surfaces are plastically deformed between indenting dies, and the thickness of the metal is reduced appreciably, to make a weld. In butt welding, the plastic flow, and thus an expanding area of contact, is produced by the upset created by pressure along the axis of the material.

Cold Pressure Lap Welds

Indented lap welding was the first of these two techniques to be established; it is perhaps the more interesting, as it has been applied to a greater variety of metals than butt welding, although the latter can be considered the superior technique.

Materials and preparation

Most success has so far been achieved in lap welding with aluminium, aluminium alloys, and copper. However, the process is not limited to these materials, and metals can be classified in regard to their suitability for the process by taking as a figure of merit the following:

$$\text{Figure of merit} = \frac{\text{Final thickness}}{\text{Twice original thickness}} \times 100.$$

Alternatively, the percentage reduction required to make a weld may be used as an index of weldability. The values given in Table I, which was drawn up a considerable time ago, are accurate enough for general

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Table I

Cold pressure weldability of materials

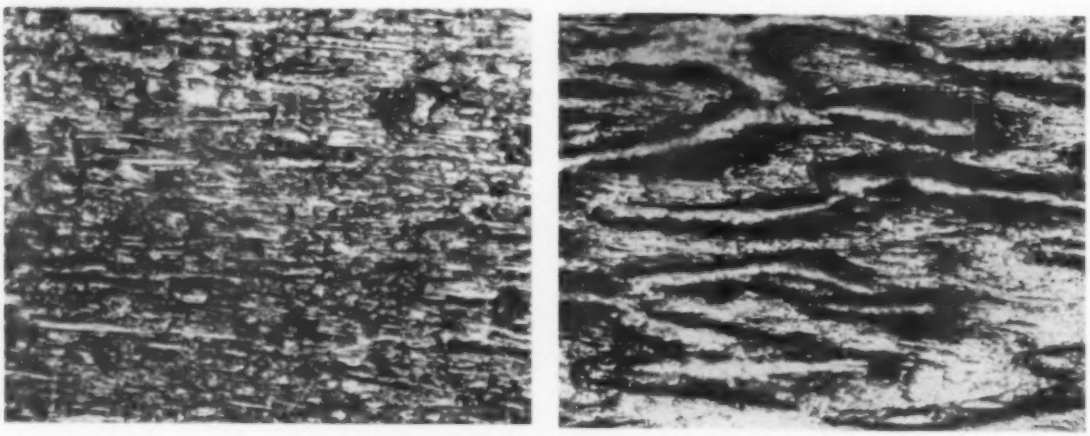
Material	*Reduction,%*	*Figure of merit*
Aluminium, super-purity	60	40
Aluminium, commercial purity	70	30
Aluminium alloys	70–80	20–30
Copper	80	20
Cadmium	84	16
Lead	84	16
Beryllium–copper	85	15
Nickel	89	11
Zinc	92	8
Silver	94	6

guidance; it should be mentioned however, that they do not quite agree with those of Tylecote.*

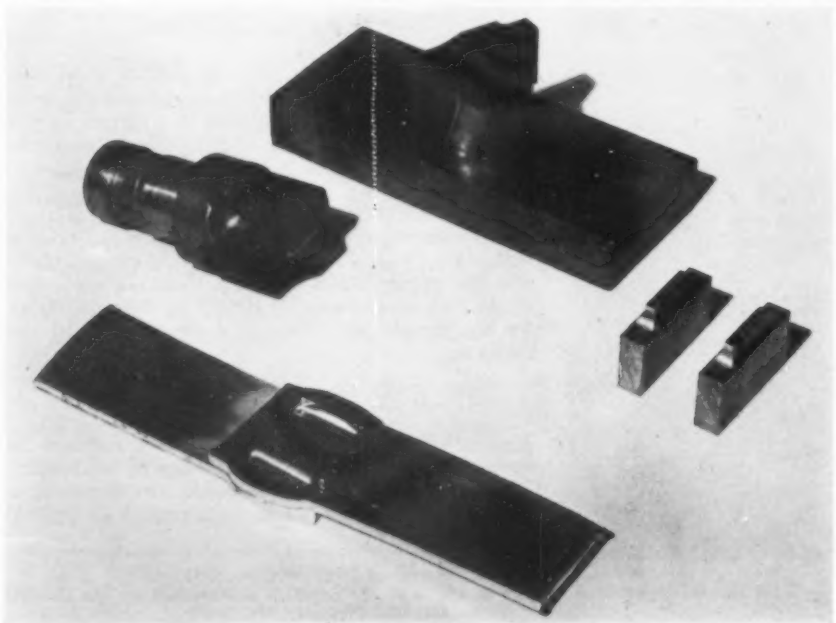
*R. F. Tylecote, D. Howd, and J. E. Turmidge: *Brit. Welding J.*, 1958, vol. 5, p. 21.

Although the surfaces to be welded may be cleaned by chemical as well as by mechanical means, the best method is by a rotary scratch brush. Experience has shown that rotary brushes made from 0·004 in. dia. stainless- or alloy-steel wire, and having a surface speed of about 3000 ft/min, produce suitable surfaces for pressure welding. Softer brushes tend to burnish the surface, and coarser ones to remove excessive amounts of metal. Typical scratch-brushed surfaces are shown in Figs. 2*a* and *b*. There is evidence that, in the surface treated with a coarse brush (Fig. 2*b*), melting may have taken place; this condition is generally considered to be undesirable.

It should be mentioned that cold welding may be achieved without cleaning the surface by scratch-brushing, if a very high reduction is applied or, in the case of aluminium, if the surface is anodized. This aspect will be discussed later.



(a) *Fine wire brush;* 2—*Surface of aluminium sheet prepared by scratch-brushing* (b) *coarse wire brush*

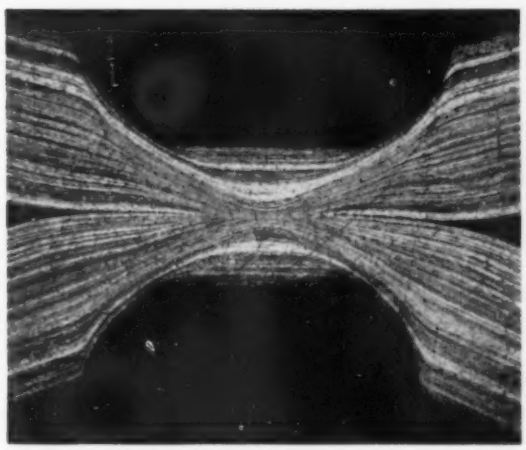


3—*Indenting dies for cold welding aluminium sheet*

Welding die design and weld strength

Indentation of the material may take place from one or from both sides of the superposed metals, depending on the particular requirements of the joint. Typical twin opposed indenting dies, and the resultant weld in commercial-purity aluminium sheet, are shown in Fig. 3. The dies are of rectangular shape, and the dimensions of the indentors are related to the sheet thickness.

Such an indent weld (Fig. 4) shows several interesting features. There is complete continuity across the weld interface, and the flow lines of the plastically deformed metal can be seen. Although the surfaces of the indenting dies are flat, there is evidence of a semicircular pressure front, as indicated by the flow lines. Where the two pressure fronts meet there is considerable local deformation. Adjacent to the tool face there



4—*Transverse section of indented cold weld* × 20

is a zone which appears to have remained stationary. Hardness values taken across the weld do not vary appreciably.

Originally the indenting dies used were hemispherical, the curved surface being presented to the work. These were replaced first by flat-faced cylindrical dies, and finally by flat-faced rectangular dies, as it was found that the weld-strength/deformation ratio could be improved by using the latter.

Three factors must be considered when designing welding dies: the length and breadth of the die, and the degree of die penetration. Within certain limits, for a given material, the weld strength will increase as the length and breadth of the die are increased, owing to enlargement of the weld area.

It is perhaps not obvious that the shape of the curve relating weld strength to percentage deformation may vary considerably for different indenting die widths. Considering first such a curve for one particular indenting die (Fig. 5) and its relationship to the mode of failure when the welds are tested in shear, it will be seen that failure of the weld can occur in three forms: (*a*) at the weld interface, (*b*) at the weld/parent-metal junction, or (*c*) through the reduced section of the weld. These modes of failure generally correspond to the regions *A*, *B*, and *C*, of the curve in Fig. 5. Welding commences at about 40% reduction, and the strength increases linearly until 60% reduction is reached (region *A*). The curve then levels off, and the weld strength decreases slowly until 85% reduction is reached (region *B*). At this point the slope of the curve changes abruptly, and the strength of the weld diminishes with increasing deformation (region *C*).

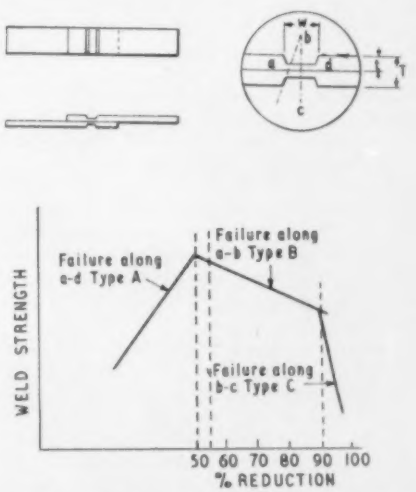
Increasing the die width shifts this curve to the left, indicating that welds can be made at a lower percentage reduction. Unfortunately, however, region *B* of the curve tends to disappear, and the weld strength now declines very sharply with reduction of the metal thickness. For this reason the use of wide welding dies is not recommended, owing to the necessity of holding the percentage reduction to a critical value.

Experiments carried out to determine the effect of die length on weld strength show that the optimum value is reached when the indentor length is six times the single-sheet thickness.

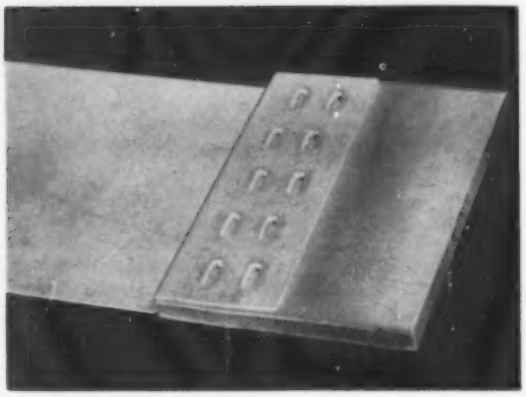
Using indenting die dimensions of width $2t$ and length $6t$, where t is the single-sheet thickness, a weld efficiency of 55% can be obtained with 99·5% purity aluminium. A similar efficiency can be obtained for aluminium ranging from 99% to 99·99% purity. Welds in annealed NS.3 and NS.4 have slightly lower weld efficiencies.

Single-sided indent welds

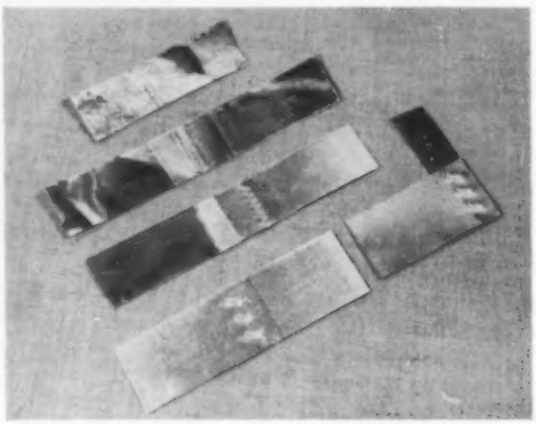
Where it is required to join metals of considerable difference in thickness, for example in the joining of foil to plate, or where the surface of one side of the material must remain relatively undisturbed, a single indentor and a flat anvil may be used to make a pressure weld. Figure 6 shows a single-sided indent weld between 22 s.w.g. and $\frac{1}{4}$ in. thick aluminium plate made in this way. To achieve a weld, the depth of the die penetration must be twice that used with twin dies. The increased deformation occurs in the metal adjacent to the indentor, which is usually the thinner sheet in welds between dissimilar thicknesses.



5—*Relationship of weld strength and percentage reduction for indented lap welds in aluminium sheet*



6—*Single-sided indent weld between 22 s.w.g. and ¼ in. thick aluminium plate*



7—*Indented lap welds in aluminium and copper foil and sheets, ranging from 0·00028 in. to 0·032 in. thick*

The resulting welds are generally of lower strength than those obtained with twin opposing dies.

Multiple indent welding

Indent welds have been made in commercial-purity aluminium ranging from foil 0·00025 in. thick to plate ⅜ in. thick. The form of the weld indentor will vary with the material thickness; for thin foils, from 0·00025 in. to 0·002 in. thick, a multiple indenting die is used, giving a very large number of closely spaced indents (*see* Fig. 7). As the material thickness increases, the size of the indentor and the pitch between the welds also increase progressively. The specimens illustrated in Fig. 7 range from foil 0·00028 in. thick to sheet 0·032 in. thick.

It is important when using the multiple weld technique that the distance between welds is such that there is no restraint on metal flow between adjoining welds, as this would seriously interfere with the mechanism of bonding. Another important feature is the distance of the weld from the sheet edge. If the indent is made too close to the edge of the material, excessive lateral flow of the metal may occur; this may also interfere with the making of the weld, and result in excessive local deformation. The pitch and edge distance of the indents can be related to the thickness of the metal, and for aluminium it should be about $5t$–$6t$, where t is the single sheet thickness.

Welding dissimilar metals and anodized sheets

When dissimilar metals, such as aluminium and copper, are to be welded, due regard must be paid to the relative hardness of the two materials. If opposing dies are used, the die against the aluminium should have a larger surface area than that against the copper. This is necessary to promote uniform flow of the two metals, the ratio of the die areas being approximately equal to the ratio of hardness. When single indentors are used, it is common practice to indent through the harder material and use a flat anvil against the softer metal.

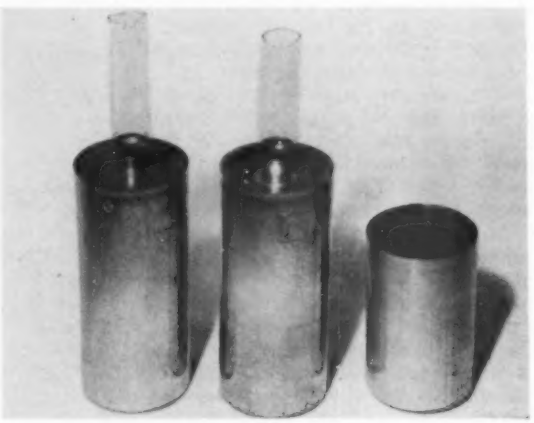
Although at one time it was considered that oxide films on the surface of aluminium were the principal barrier to cold welding, it has since been found possible to make welds between anodized aluminium sheet or foil without further surface preparations. Preliminary tests have indicated that an anodic film 2–6 μ thick is satisfactory. Advantage has already been taken of this technique in the electrical industry, where anodized aluminium strip is used for electrical windings, the anodic film being a good insulator. Welds between anodized strip and copper can be made very easily with a simple hand tool.

Tests to compare the strengths of welds in anodized material and scratch-brushed material show that there is only a 10% reduction in strength in using anodized material.

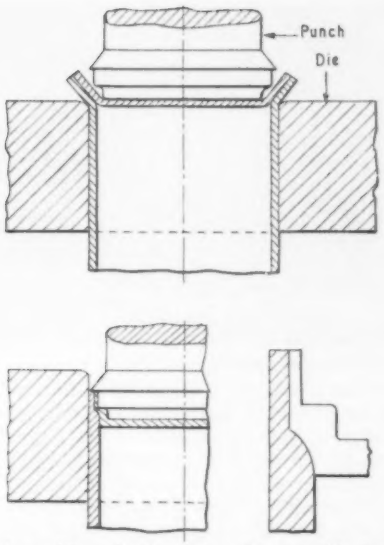
Extrusion welds and seam welds

It is sometimes necessary to weld lids to circular or elliptical cans without the flanged edge preparation normally used with the indent weld technique. One example is a cold-welded condenser can, where the diameter of the welded lid was not to exceed the diameter of the can.

To achieve this, the extrusion weld was developed; an example is shown in Fig. 8, where a copper lid is welded to an aluminium can. Both the lid and can are



8—*Extrusion welds between extruded aluminium cans and copper lids*

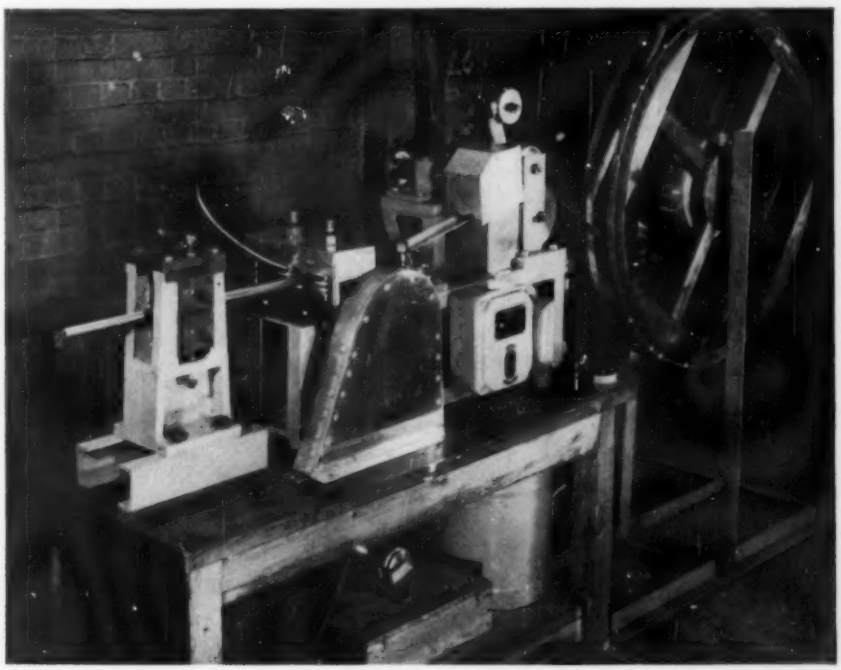


9—*Extrusion welding, showing action of tools and (enlarged) the form of the resultant weld*

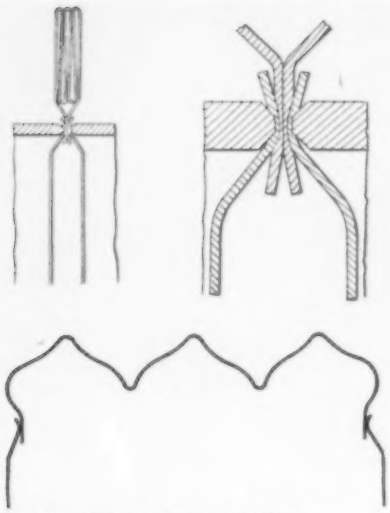
coned before welding. The two parts are fitted together, and inserted into a ring die having a bore diameter slightly larger than the outside diameter of the can. The lid and can are then pushed through the die by the punch, which has a stepped shoulder (Fig. 9). The metal of the coned ends is extruded upwards by the action of the punch, and the excess is sheared off by interference between the cutting edge of the punch and the ring die face. The resultant pressure weld is also shown, diagrammatically, in Fig. 9.

10—*Transverse section of cold-welded aluminium cable sheath*

This technique has been applied to the welding of aluminium and copper in similar and dissimilar metal combinations.



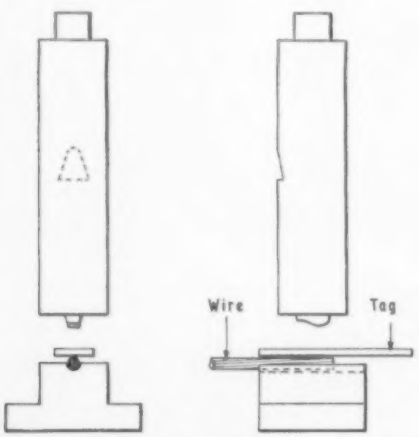
11—*Experimental cable sheath forming and welding machine*



12—*'Sandwich' welding technique*

Indent seam welds may be made continuously by passing the work through circular indenting wheels. It is common practice when using this technique to combine with the welding operation any forming operation that may be required. A typical example of this method, which has been applied to the sheathing of cables with aluminium and in the manufacture of tubing, is illustrated in Fig. 10, showing a transverse section of the formed and welded sheath. Here, the flanged edges of the formed sheath are passed through double indenting rolls which weld and trim off excess metal simultaneously. An experimental aluminium sheathing machine is shown in Fig. 11; this is employed in sheathing polythene and P.V.C. insulated cables. The absence of heat in the welding process is of great importance, as the sheath may be a close, or interference, fit over the plastic-insulated core.

This technique has also been used for rubber-insulated cables for domestic wiring and for paper-insulated power cables.



13—*Dies for cold welding stranded aluminium wire to aluminium cable lug*

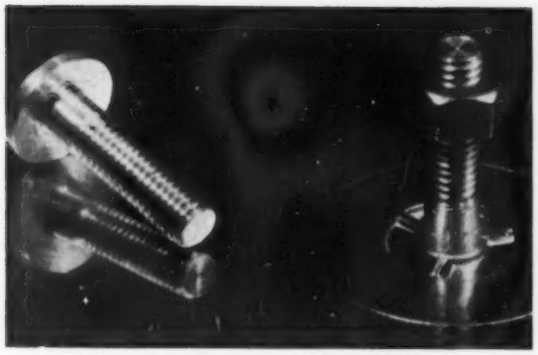
14—*Cold-welded aluminium cable lugs*

Other techniques and applications

It is often required to make welds through several thicknesses of sheet simultaneously, at the same time controlling the number of surfaces that weld together. This may be achieved by coating the surfaces that are not required to weld with a non-brittle lacquer or other barrier film. Sometimes the inherent surface film on the material is sufficient to prevent welding from taking place. A typical example of such 'sandwich' and selective area welding is shown in Fig. 12. Here a number of sheets are indented simultaneously, the inner surfaces having a barrier or weld-inhibiting film. After indenting, the surfaces may be separated as shown in the lower part of the illustration.

Cold welding may also be used to join stranded conductors to connecting lugs or tags. The technique employed is to rest the cleaned strands in a semi-circular die, and indent from one side through the connecting tag (*see* Fig. 13). Figure 14 shows how the conductor strands have bonded together and to the aluminium tag. Tests carried out to determine the electrical conductivity of the welds showed that the resistance was 66% of that of the stranded conductor. The principal difficulty of applying this technique is

15—*Aluminium kettle fabricated by cold welding two half pressings*



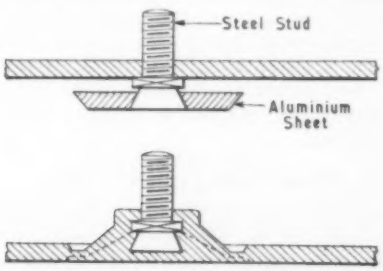
16—*Aluminium stud welding*

that the wire strands must be separated and cleaned before welding.

The ability of cold pressure welds to stand up to arduous conditions is emphasized by the application of the process to domestic utensils. Cold-welded aluminium kettles, made up of two half pressings welded on the body centre-line (Fig. 15), have been in service for over eight years.

Another example of the application of cold welding is illustrated in Fig. 16, where aluminium-alloy studs are welded to commercially pure aluminium sheet using indenting dies.

Steel studs or nuts may also be secured to aluminium sheet by the 'trap weld' technique (*see* Fig. 17). In the example illustrated, a steel stud with a conical head is encased in aluminium by the plastic flow of

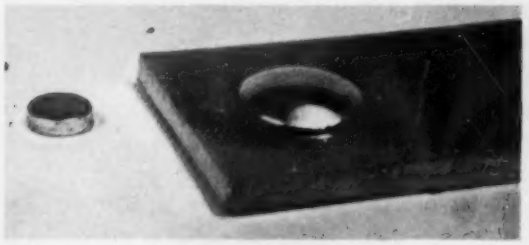


17—*'Trap weld' technique for attaching steel studs to aluminium sheet*

the material brought about by indenting dies. The aluminium for encasing the stud is provided by a disc or pellet placed on the side of the sheet opposite to the threaded portion of the stud, and welded to the sheet.

The joining of precious metal contacts to relay and switch components often presents welding problems. These contacts, which are generally joined by riveting, brazing, or resistance welding, may in some instances be cold welded. Figure 18 shows a silver contact cold-welded to a copper strip by means of a single-sided indentor applied through the copper. Advantage has been taken of the plastic flow involved in welding, to form the silver contact into a hemispherical shape at the same time.

The most important use of indent and extrusion welding techniques at the present time is in the canning or incapsulation of crystal devices, the germanium or



18—*Silver contact welded to copper strip*

silicon diodes and transistors. This method of sealing metal envelopes and cans is ideal, as the crystal devices are thermally sensitive. Cold welding is finding universal application for this purpose, and has been a valuable contribution to the development of these important electronic devices. In the medical field, cold welding has been used in the manufacture of ionization monitor chambers for use with deep-therapy X-ray equipment.

Some highly successful applications of cold welding have been made in nuclear engineering. One of these is the welding of an 80/20 brass bellows to a cast aluminium ring for high-vacuum applications.

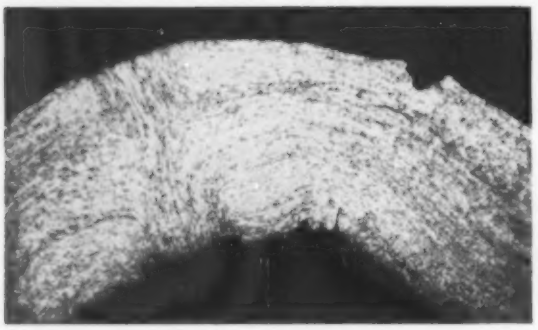
Cold Pressure Butt Welding

Butt welding is the superior of the techniques used in cold welding; it fulfils most of the requirements of a perfect weld; namely, continuity, homogeneity, and properties closely allied to those of the parent metal.

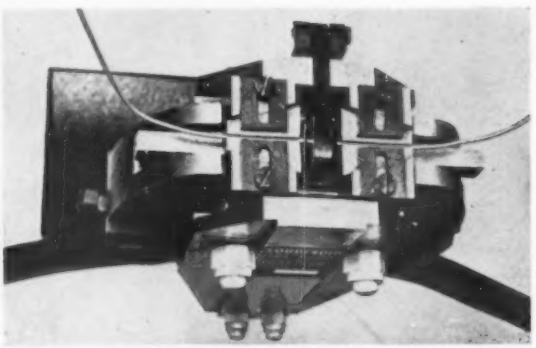
Butt welds may be made between rod, tube, wire, sheet, and strip components. The technique consists of holding the parts to be welded in split clamping dies so that there is a length projecting from the die face square to the material diameter or thickness. Pressure is then applied, and lateral flow is allowed to take place until the material projecting from the die face is reduced to about one-quarter of its original length. In the case of wire or rod, the plastic deformation of the metal results in a circumferential upset, as illustrated in Fig. 19, which shows a weld as made and one after the excess upset metal has been removed.

Preparation of the surfaces for welding consists of squaring the ends of the material by shearing or filing. With some of the high-strength aluminium alloys it has been found preferable to scratch-brush the ends of the material after shearing; this is probably needed to remove contaminants from the weld area, which are transferred from the surface of the material during the shearing process.

19—*Butt-welded aluminium rod; as-welded, and after removal of excess metal*



20—*Transverse section of butt-welded aluminium rod, sectioned after reverse bend test* ×50



21—*Stored-energy wire butt welder*

A photomicrograph of a butt weld in commercially pure aluminium rod is shown in Fig. 20. This weld has been sectioned after being subjected to a reverse bend test, and it will be seen that the metal is failing outside the weld area.

Materials and techniques

Butt welds may be made in commercially pure aluminium, NS.3 and 43 S aluminium alloys in all tempers, whereas NS.5 is limited to the half-hard condition and NS.6 to the fully annealed condition.

Copper may be welded in both annealed and hard-drawn condition, but the cadmium–copper alloys are only weldable when fully annealed.

Close tolerances must be maintained for the gripping jaws of butt welding machines. An interference of 0·002–0·004 in. between the rod or wire and the gripping jaws is required to prevent the work piece slipping when subjected to welding pressure.

Wires ranging from 0·030 in. to 0·160 in. dia. can be welded by hand-operated tools; for larger diameters, power-operated tools are used. Rods up to $\frac{5}{8}$ in. dia. have been welded using hydraulically operated tools.

In France, the licensees of the author's company have a preference for stored-energy butt welders giving impact loading (*see* Fig. 21); energy is stored in compression springs which act upon the welding dies to give the upsetting force. Experience of the author's company, however, is that impact loading itself is not as important as maintaining continuous pressure during welding, and that any relaxation will interfere with the making of the weld.

Cold welding may be used to butt weld aluminium strip ranging from 0·008 in. thick by $\frac{7}{16}$ in. wide to 0·048 in. thick by $5\frac{1}{2}$ in. wide. Butt welds may also be made between rod and sheet, and may be used in the joining of thick-walled tube. In the latter case, an internal mandrel must be used to control the metal upset.

Properties of butt-welded wires

The mechanical and electrical properties of butt welds are excellent in both similar and dissimilar metal welds.

Tests carried out to compare the mechanical properties of cold welds and resistance butt welds in $\frac{1}{2}$-hard commercially pure aluminium, show that cold welds have weld efficiencies of 98–100%, whereas resistance butt welds have only a 50% efficiency. Voltage-drop tests on pressure-welded wires have failed to detect any increase in resistance at the weld.

The use of cold pressure butt welding by the electric cable industry is growing, as it is possible to make welds in hard-drawn and heat-treated materials without a reduction in mechanical properties at the weld. Welds made in the magnesium silicate heat-treatable aluminium alloys, for high-tensile overhead cable lines, also show great promise.

Welding copper to aluminium

Copper and aluminium may be cold-welded to form tubular members either by the welding of thick-walled tubes or by drilling out butt-welded rods. These welded tubes are being used in conjunction with roll-bonded aluminium refrigerator evaporators, where it is necessary to connect the aluminium evaporator to a copper pipeline system. The aluminium end of the tube is argon-arc welded to the evaporator and the copper end is silver soldered into the copper piping system. These copper-to-aluminium cold pressure butt welds compare very favourably with flash-butt welded bi-metal tubes.

Future Trends in Cold Welding

It is believed that the application of cold welding will increase considerably, and the process will be enhanced if the critical values of deformation can be reduced and the process made less sensitive to surface preparation.

The ability to weld through anodic films on aluminium will no doubt be of assistance in this direction. There are indications that both magnesium and titanium alloys may ultimately be welded, and information from the United States reveals that the butt welding of large cross-sections of aluminium alloys is now being accomplished.

The development of ultrasonic welding may have some effect on the progress of cold pressure welding, but it is the belief of those people closely connected with the process, both in Britain and the U.S.A., that cold welding will be the recognized method of joining aluminium and copper in the future.

There are many gaps to fill in the knowledge of the fundamentals of cold welding, and it is hoped that the excellent research work being carried out at the University of Birmingham and other universities will help to remedy this situation.

PRESSURE WELDING BY ROLLING

By L. R. Vaidyanath,

M. G. Nicholas,

and D. R. Milner

The mechanism of pressure welding as it is operative in roll bonding has been investigated. A test has been devised and bond strengths measured for aluminium, copper, lead, tin, and zinc welded at room temperature. In all cases a 60–70% reduction in thickness was required to approach maximum bond strength, although the threshold deformation required for the initiation of bonding varied. A theory is proposed for the maximum strength that can be attained on the assumption that bonding is prevented by the presence of the oxide film, and that at an early stage in the progress of the composite through the roll gap the two oxide films come together and thereafter behave as one. The virgin metal area of potential bonding is then given by the increase in area of the interface, and taking account of the triaxiality of stressing this results in a maximum ultimate shear strength given by: $U.S.S._{weld} = R\ (2-R)\ U.S.S._{solid\ metals}$ *where* R *is the reduction in thickness of the composite.*

However, there are many conditions under which this maximum strength is not achieved, since the virgin metal areas do not always join. Hence the initiation and development of bonding has been studied and was found to be promoted by increasing the pressure, increasing the temperature, increasing the roll diameter and decreasing the roll speed. Prolonged exposure of the surfaces before rolling led to the formation of adsorbed layers of water vapour which inhibited welding. This information has been related to the possible mechanisms which could control bond formation; it is concluded that a correct model must involve considerations of atomic movements during deformation, local readjustment at the interface by diffusion processes, and the solution of entrapped gases.

Introduction

AMONG the welding processes, pressure welding is regarded as a relatively specialized technique, applicable only to specific types of joining problems. For this reason it has not been extensively investigated, although the important factors and the conditions of application of the process have been fairly well defined empirically. The mechanism of bonding is not clear despite a number of researches into the subject, and various workers have postulated that it is dependent on a variety of different factors. The present investigation, while it may contribute to the relatively limited data available on the practice of roll welding, has been primarily concerned with the mechanism of bonding, and the experimental approach has been chosen with this end in view.

The present state of the practice and theory of pressure welding has been reviewed in the first paper in this series by Professor E. C. Rollason; the factors of temperature, pressure, degree of deformation, oxide break-up, flow of surface asperities, and elastic recovery have all been shown to exert a marked influence on bonding, and some workers have proposed that one factor in particular controls the process. Since the advocates of the importance of a specific parameter can produce considerable supporting evidence for their ideas, it is probable that the controlling factor will be shown to vary with the conditions of welding.

A preliminary analysis of published information led to three conclusions. Firstly, whilst the importance of many factors has been demonstrated, for instance, surface preparation before welding, the inherent basic parameter (which might, in this example, be oxide film thickness, surface roughness, or the presence of adsorbed gas layers), is not always obvious, and cannot be evaluated because information gained from the various welding systems can not be correlated. Therefore, before carrying out an analysis to decide on the model that has to be developed for an understanding of the mechanism of pressure welding, it is necessary to amass a body of relatable data on one simple welding system. Secondly, whilst the purpose of pressure welding investigations is to determine the processes that control bonding, no really satisfactory test method has been set up for the measurement of bond strength,

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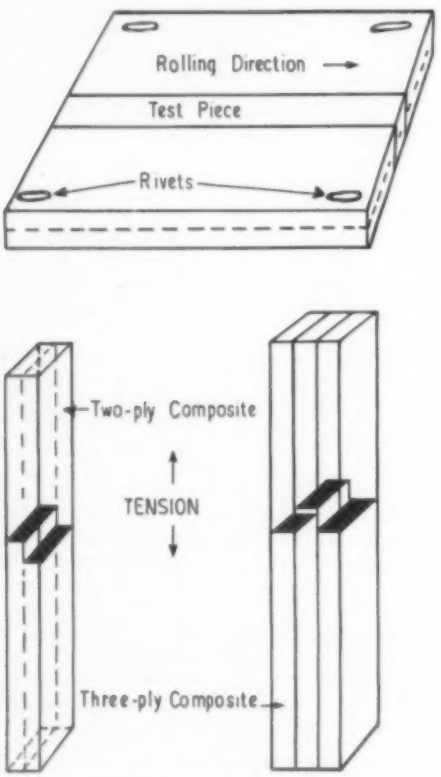
and some of the techniques used, particularly for small-tool welding, give results which are in fact misleading. Thirdly, a major difficulty in the study of the mechanism of pressure welding is that it is linked with the complex problem of metal flow and deformation patterns in metal working. Thus, whereas the formation of a bond between two metal surfaces is likely to be dependent on such factors as the presence of oxide or other films, and the closeness of approach of the two surfaces, the degree of oxide break-up and the deformation system will depend on the shape of the deforming tool. It is therefore important to separate, as far as is possible, the study of bond formation across an interface from the problem of the plastic flow of metals under various tool shapes, as this is a major field of study in its own right.

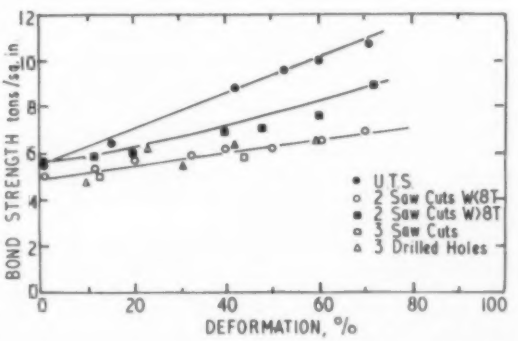
Pressure welding by rolling was therefore chosen as the most suitable system for investigation, because the deformation pattern is simple and is reasonably well understood. In addition, for this method a test could be envisaged, the results of which would be more amenable to analysis than in other cases. Using the roll bonding technique and this test the mechanism of pressure welding is being investigated, and this paper describes the first phase of this work, which has been concerned with the welding of similar metals at room temperature. Complementary to the determination of bond strengths, a microscopic survey has been made of the characteristics of weld interfaces. The results obtained have led to a model which explains the role of the oxide film and allows the calculation of the maximum bond strength that can be obtained for any given deformation. However, under many circumstances there is no bonding, or the maximum strength attainable is not achieved; no positive contribution can be offered to the solution of this problem, but the evidence is assessed to show the factors which a correct theory would have to take into account.



1—*Test to determine bond strengths*

Measurement of Bond Strength

A satisfactory test should measure the strength of pressure welds by a method that allows comparison with the inherent strength of the metal. This can be done for roll welded material by using the test shown in Fig. 1. A test strip, about $\frac{1}{2}$ in. wide and at least 0·2 in. thick, is cut from the rolled composite, and saw cuts are made so as to isolate an area which is then tested in shear by pulling the test strip in tension. Originally it was thought that, to get a true shear strength result, it would be necessary to work with triple composites so that the stress conditions would be symmetrical and thus eliminate any twisting of the specimen and the consequent introduction of a tensile component. To isolate the test area with the triple composites, a central cut was made by drilling a small hole and then cutting outwards with a jeweller's saw; the alternative of isolating the area under test by three drilled holes was found to be equally satisfactory, although the accurate delineation of the area was more difficult in this case. However, working with triple composites is tedious, and it was found that the same results could be achieved with duplex specimens, provided that the length, W, of the area under test was not more than 0·8 of the total thickness, T, of the composite, so that no twisting or tensile component was introduced. For the testing of relatively weak joints, the length of the area under test can be considerably increased without the introduction of a tensile component, and in fact, to obtain accurate values of low bond strength, this is advisable. To evaluate very low bond strengths, it is essential to increase the length under test, as a small area often provides insufficient strength for the joint to withstand the most careful handling. A final composite thickness of 0·2 in. was



2—*Comparison of the strength of aluminium determined by symmetrical and asymmetrical methods of isolating the area under test, and U.T.S. as determined by normal tensile tests*

found to be advisable, otherwise the location and extent of the saw cuts presented difficulties.

The major advantage of this test is that it permits a comparison with the strength of solid metal which has undergone the same working treatment; throughout this work the general practice has been adopted of rolling a two-ply composite, and a solid piece of metal of the same overall thickness and in the same state of hardness, and then comparing the strengths obtained. Figure 2 shows the strength of solid aluminium as measured by this test for both duplex and triple specimens, and gives also the ultimate tensile strength of the material as determined from conventional tensile tests. The meaning that can be ascribed to the results of a test of this nature cannot be precise because of the nature of plastic flow, but the generalization of Sachs and van Horn,[1] that 'The shearing strength of most wrought metals and alloys ranges from 55% of their tensile strength for severely cold worked metals to 75% for the annealed soft condition', fits very well the results obtained by the present test.

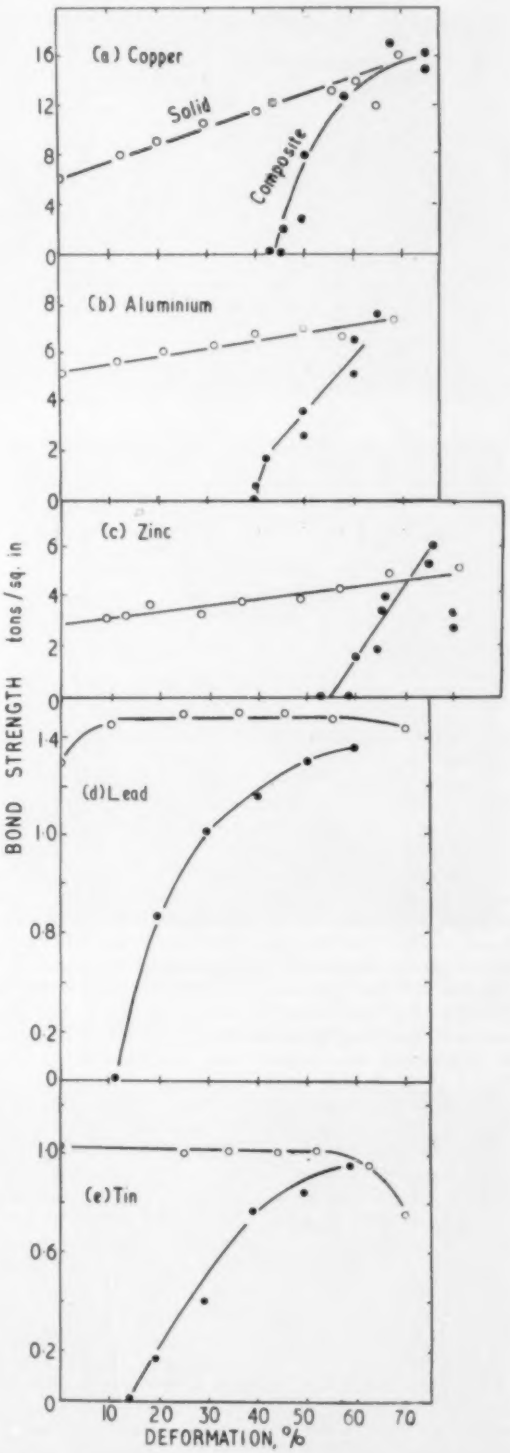
Results of Bond Strength Determinations

Using the test described, bond strengths were measured and compared with solid metal strengths for fully annealed aluminium, copper, tin, lead, and zinc rolled at room temperature. Composites measuring 4 × 4 in. were degreased in trichlorethylene vapour, scratch-brushed, pinned in the corners with rivets to prevent separation in the roll gap, and were rolled, within 2 min of the scratch-brushing treatment, in an 18 in. dia. two-high mill at 200 ft/min. To obtain the necessary 'bite' with high deformations, the rolls were degreased and treated with magnesia powder. The bond strength was then determined at the centre of the composite; the results obtained are shown in Fig. 3.

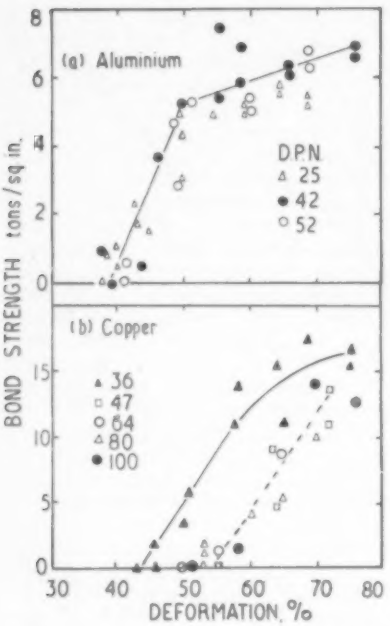
Attempts to weld magnesium at room temperature showed that no bond strength could be obtained with up to 50% deformation, and the metal disintegrated at higher deformations.

When cutting out the specimens for testing, it was found that there was a difference between the degree of deformation at which the two members of the composite appeared to adhere, and the deformation at which a specimen could be isolated without the joint breaking. Since this difference was not eliminated by the most careful handling and cutting-out techniques, it was concluded that it was due to the readjustment of the residual stress system, leading to a stress in the joint area, as each cut was made in the composite during the process of isolating the test area. Thus, for example, with aluminium the composite would have apparently adhered at a deformation of 35%, whereas no positive bond strength could be obtained for deformations less than 40%.

These bond strength determinations showed that in all cases the solid metal strength was reached at about 60–70% deformation, whereas the threshold deformation for bonding varied from one metal to another. This means that for roll bonding, at least, it is not entirely adequate to state that one metal welds more readily than another, since they all require 60–70% deformation for maximum strength; rather, welding



3—*Bond strength as a function of deformation for copper, aluminium, zinc, lead, and tin, and strength/deformation curves, determined by the same test, for solid metal*



4—*Effect of various degrees of pre-straining on the welding of* (a) *aluminium and* (b) *copper*

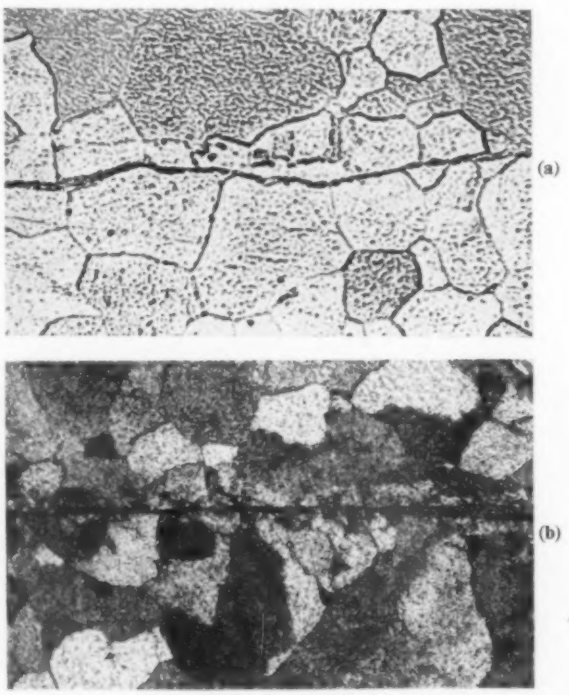
can be initiated more readily with some metals than with others.

Since a theory of the mechanism of pressure welding must explain the different deformations required for the initiation of bonding, any trend that can be observed may provide a pointer to the correct model. Two possible causes are immediately obvious for the variation of the threshold deformation: it could increase either with the increasing melting point of the metal, or with the hardness. The latter possibility conflicts with the results of Pugh,[2] and later Tylecote *et al.*,[3] who showed that increasing the hardness of a metal by pre-straining made small-tool welding easier. For this reason, the effect of pre-straining on the bond strengths in aluminium and copper was investigated; it was found (Fig. 4) that with aluminium increasing the initial hardness had no effect, whereas with copper it made welding more difficult. Since a repeat of the small-tool welding work confirmed the results of the other workers, it was concluded that their results were not fundamental to a mechanism of pressure welding but specific to small-tool welding, and were probably due to an alteration in the deformation pattern and/or the joint area. Unfortunately, it was not possible to extend the roll bonding investigation, with 4 × 4 in. specimens, to include harder metals such as iron and nickel, because of the limiting load-carrying capacity of the rolling mill (200 tons); with smaller specimens (1 in. wide and 0·2 in. thick), it was found that the threshold deformation for Armco iron was 62%, but as will be shown later, welding is not independent of specimen size, so that this result is not strictly comparable with the rest of the series.

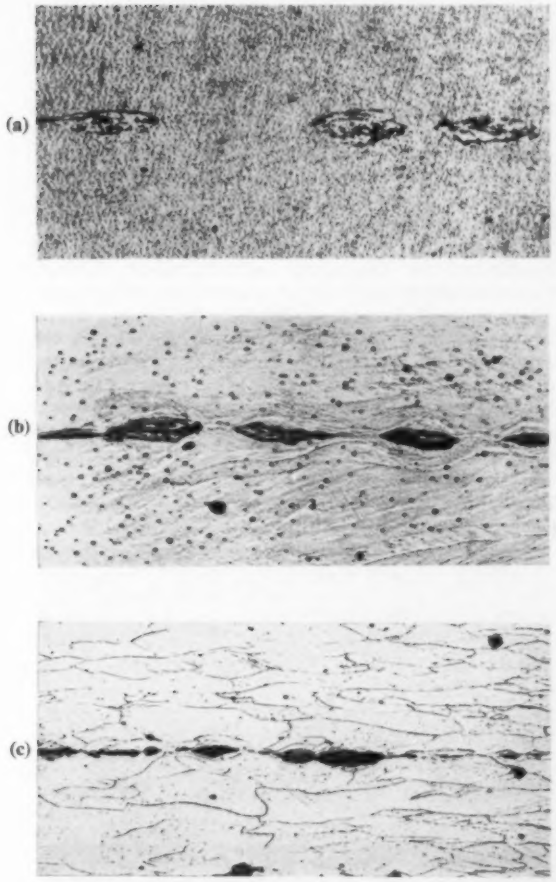
Bond strengths at very high deformations were difficult to obtain, because the mill would not bite on the specimen and rejected it. To some extent this could be overcome by chamfering the leading edge, but because of this problem, and the fact that when dealing with harder metals less strain would be imposed on the mill if the deformation could be given in several passes instead of in one pass, the use of a multi-pass rolling technique was investigated, using aluminium and copper. It was found that no bonding could be obtained unless the first pass was sufficient to initiate welding, but thereafter substantially the same bond strength was achieved by multi-pass as by single-pass rolling.

Microscopic Examination of Weld Interfaces

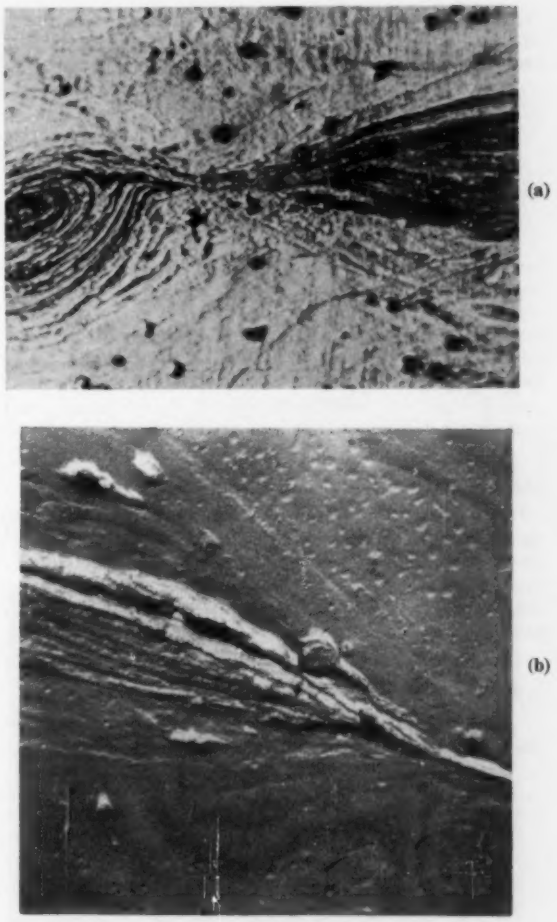
Sections taken from the centre of typical composites (corresponding to the region in which the bond strength determinations were made) were subjected to a microscopic examination and it was found that the weld interfaces could be divided broadly into two types. The first type, which occurred with tin and lead, (*see* Fig. 5), showed a continuous boundary; the second type, characteristic of aluminium, copper, and the narrow Armco iron specimen (*see* Fig. 6), showed a discontinuous interface, having regions of apparently bonded metal interspersed with what have, for reasons which will become clear later, been called primary discontinuities. Zinc appeared to be an intermediate case, in that it showed both types of boundary in different regions of the joint interface. In no case was grain growth across the interface observed, although tin and lead had of course completely recrystallized.



5—*Continuous type weld interfaces*: (a) *tin boundary, 60% deformation, × 250, etch 5% HCl in alcohol;* (b) *lead boundary, 20% deformation, × 90, etch fuming* HNO_3



6—*Discontinuous type weld interfaces*: (a) *aluminium boundary, 55% deformation, ×250, etch 5% NaOH;* (b) *copper boundary, 64% deformation, ×450, etch NH_4OH/1% H_2O_2;* (c) *Armco iron boundary, from specimen initially 1 in. wide by 0·2 in. thick, 64% deformation, ×270, etch 2% Nital*

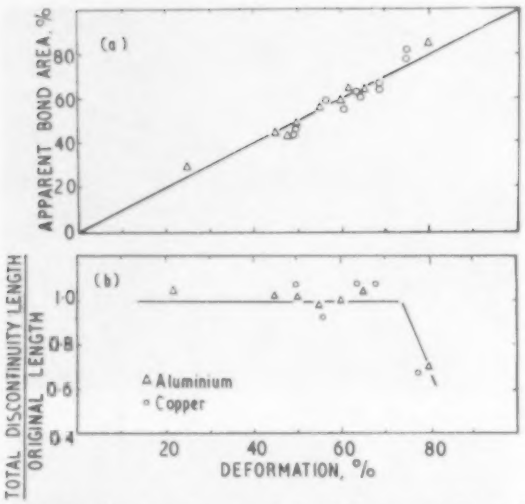


7—*Primary discontinuity in copper showing the heavily worked structure;* (a) *oil immersion micrograph ×2000, etch NH_4OH/H_2O_2;* (b) *electron micrograph, ×3500; note the unwelded section of the interface*

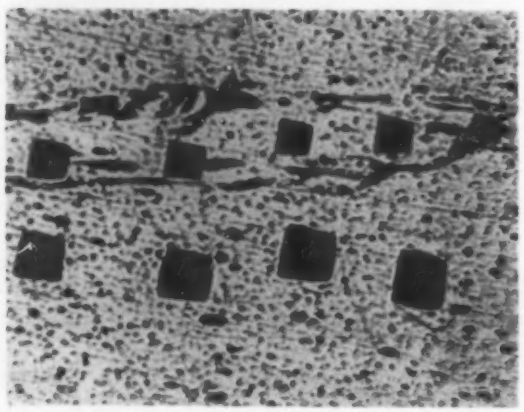
In regard to the metallographic technique in this work, conventional emery rough preparation was used, followed by diamond dust polishing, possibly finishing with a light 'Silvo' polish. Electropolishing tended to attack the inclusions very heavily, thus giving the misleading impression that the interfaces consisted of a series of voids. To a lesser extent, prolonged etching or deep-etching reagents lead to similar misleading results.

To learn more about the structure of these boundaries, the investigation was extended to higher magnifications, in one case (copper) using an electron microscope. At these high magnifications the discontinuities in copper and aluminium had the appearance of a heavily worked structure (Fig. 7), whereas tin and lead consisted of a very fine-grain recrystallized structure interspersed with apparent line discontinuities, (*see* Fig. 8). Since the discontinuous characteristics of the aluminium and copper boundaries lent themselves to a more detailed investigation, a survey was made of the number, size, and distribution of the

8—*Tin boundary showing fine-grained recrystallized structure, ×2000, etch 5% HCl in alcohol*



9—(a) *Development of apparently bonded area, and* (b) *total length of the primary discontinuities related to original length of specimen, both as a function of deformation*

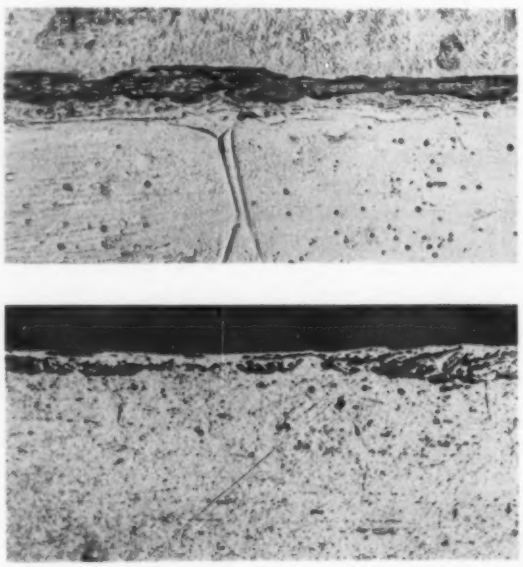


10—*Micro-hardness indentations, showing relative hardness of the primary inclusion and the adjacent metal, ×940, etch 2% HF/27% HNO_3*

primaries for different degrees of deformation. This showed that the length of apparently bonded interface increased linearly with deformation, but that the total length of discontinuity remained equal to the original length of the specimen, except for very high deformations (*see* Fig. 9). The point corresponding to a deformation of 23% given in these curves requires an explanation, since bonding in aluminium, and hence weld interfaces, cannot be obtained for deformations below 40%. In view of the difficulty in deciding the trend of results obtained over a limited range of deformation, one experiment was made in which a $\frac{1}{2}$ in. wide groove was machined along the length of a 4 in. wide specimen, which was then rolled so that, while the overall deformation was 65%, the metal in the groove only underwent a reduction of 23%. Under the microscope, a continuous crack was observed across the region of low deformation, but the specimen was held together by the bonded regions on either side and the primary discontinuities could be clearly distinguished.

Micro-hardness measurements showed the primary discontinuities to be very hard, of the order of two to three times the hardness of the adjacent heavily worked metal; typical comparative hardness indentations for aluminium are shown in Fig. 10. Measurements made on the bonded sections of the interface showed these to have the same hardness (and hence strength) as the bulk of the composite.

The identity of the primary discontinuities was established by examining sections taken through scratch-brushed surfaces of aluminium and copper, which showed that scratch-brushing produced a heavily worked layer (*see* Fig. 11) which was clearly the origin of the primary discontinuities shown in the photomicrographs taken at the same magnification in Fig. 6. The micro-hardness measurements of the worked layer were made, and the hardness was found to correspond with that of the discontinuities. This extreme hardness of the scratch-brushed layer can presumably be ascribed to the inclusion of particles of



11—*Sections taken through the layer of heavily worked metal produced by scratch-brushing*: (a) *Copper, with surface protected by electro-deposited copper, ×450, etch NH_4OH/ H_2O_2*; (b) *aluminium, ×250, etch 2% HF/27% HNO_3*

oxide, together with torn-off fragments of scratch-brush wire. There is admittedly some doubt about the accuracy of the measurements made, as the thickness of the layer limited the maximum size of the hardness impressions to within the range 0·6 to 1·6 μ, whereas the handbook[4] recommends a minimum diagonal length of 10 μ. To obtain impressions of less than 2 μ diagonal length, very low loads, of 1 or 2 g., had to be used, and this resulted in hardness values that could not be directly compared with the known macro-hardness of the materials. This difficulty was overcome by deriving a calibration curve, for the same load as used in this work, from a series of metals the

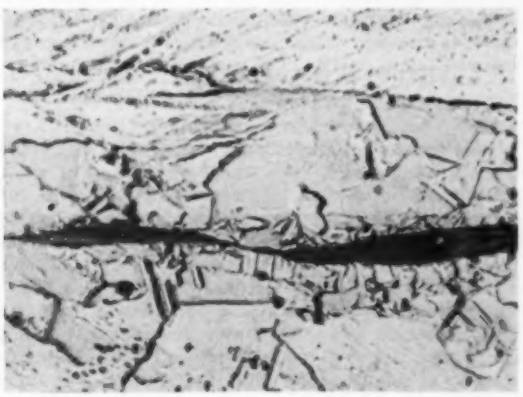
Table I
Micro-hardness determinations

Metal	*Scratch-Brushed Layer,* D.P.N.*	*Scratch-Brushed Layer, D.P.N.*	*Primary Discontinuities, D.P.N.*	*Adjacent Metal, D.P.N.*
Aluminium	130	90–110	100–120	48
Copper	180	200–230	240–280	125
Iron	600	—	850	212
Brass	210	—	—	—

* Due to Ainbinder and Klokova.

hardnesses of which were determined conventionally at normal loads. It was impossible to carry out micro-hardness determinations for the tin and lead interfaces, since even 1 and 2 g. loads resulted in diagonal lengths greatly in excess of 2 μ. The results of the micro-hardness measurements thus obtained are shown in Table I and these compare well with the only other results of similar measurements known, due to Ainbinder and Klokova;[5] the technique used by these workers was however not specified.

The conclusion reached from the examination of the primary discontinuities is that, with aluminium and copper, scratch-brushing produces a very hard and brittle layer, and that when two members of a composite are rolled together the two scratch-brushed layers come into contact and thereafter behave as one, so that the total length of layer always equals the original length of the composite. Since the oxide film formed after scratch-brushing will be formed on this layer, the position of the primary discontinuities must show the position of the oxide film. In the case of tin and lead, a scratch-brushed layer will recrystallize and deform in a ductile manner on rolling, and thus give the continuous interface observed with these metals. However, if the oxide film is brittle, it will fragment in a similar manner to the work-hardened layer, the total length of the fragments always equalling the original length of the composite. The decrease in the total length of the primary discontinuities at high deformation was due to partial recrystallization in the immediate vicinity of the interface, reducing the volume of work-hardened material, as shown by the micrograph (Fig. 12) of copper which had undergone a 75% reduction.



12—*Local recrystallization around a primary discontinuity, resulting from the heat and deformation produced by a 75% reduction in thickness, ×940, heavy etch in NH_4OH/H_2O_2*

Theoretical Determination of the Maximum Bond Strength attainable

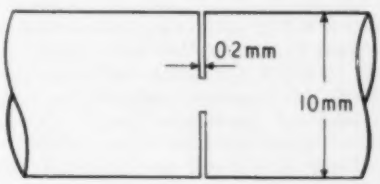
On the assumption that composites which possess an initial oxide film always deform in such a way that the two oxide layers break up as one, and in a completely brittle manner, the area of virgin metal interface which is potentially available for bonding can be calculated. And if account can be taken of the stress conditions which are operative when testing the joint, it should be possible to make a theoretical determination of the bond strength. Thus:

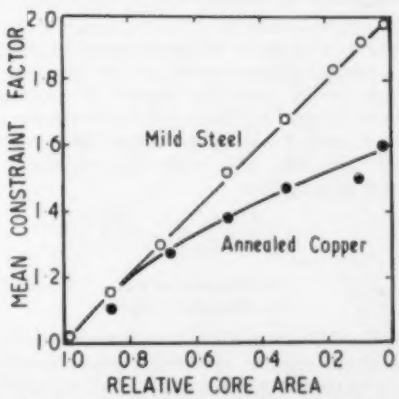
$$\text{Maximum bond strength per unit area} = \text{Metallic area created per unit area} \times \text{Strength of bonds}$$

The amount of metallic area created per unit area can be determined by considering unit width of composite having an original thickness a and length b, which is extended by rolling to length y and thickness x. Then, assuming plane strain, which is certainly true for the centre of the composite, $ab=xy$, and

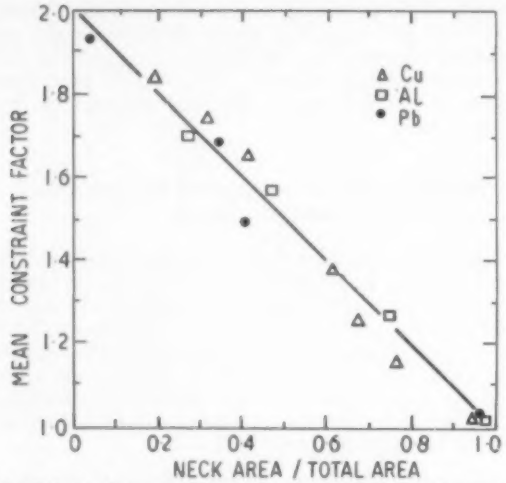
$$\text{Metallic area created per unit area} = \frac{y-b}{y} = 1-\frac{b}{y} = 1-\frac{x}{a} = \frac{a-x}{a} = R$$

where R is the reduction which the metal has undergone.





13—*Type of test piece used by Orowan, Nye and Cairns,[6] and the relationship obtained by them between the constraint factor and the ratio (area of core/ area of bar)*



14—*Relation between constraint factor and degree of restraint for lead, work-hardened copper, and work-hardened aluminium*

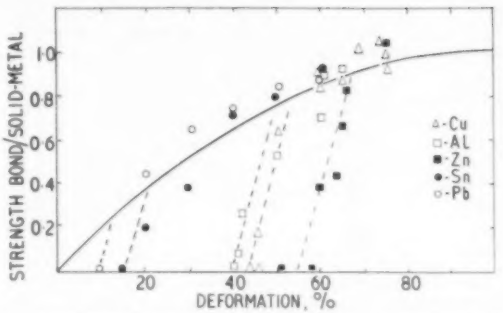
The strength of the bonds is a more difficult factor to assess, and can best be correlated with data available for stressing in tension and then applied to the problem in hand by making an assumption. If the joint is tested in tension the metallic bridges across the interface will not yield at the same stress as they would under pure tension, because of the constraining effect of the bulk metal on either side. The mechanical behaviour of a metal stressed under non-uniaxial conditions has occupied the attention of many workers, and involves the introduction of the concept of a constraint factor C, which in this case would be given by $C=(\text{U.T.S.}_c)/(\text{U.T.S.}_t)$, where the subscript c designates the U.T.S. measured under constraint and t the U.T.S. measured under pure tension. Orowan, Nye, and Cairns[6] determined the variation of C with the degree of restraint for steel and annealed copper bars, in which an area was placed under restraint by cutting an annular notch around the bar. The degree of restraint was determined by the ratio of the area of the core to the adjacent area of the bar. These workers found that the constraint factor increased linearly (*see* Fig. 13) to a value of 2 for maximum restraint for steel, and to a value of 1·6 for copper. In the present work, a similar determination of the variation of the constraint factor with the degree of restraint was carried out for lead and for work-hardened copper and aluminium, and it was found that a linear result was obtained (*see* Fig. 14), with the constraint factor increasing to 2, so that

$$C=\frac{\text{U.T.S.}_c}{\text{U.T.S.}_t}=\left(2-\frac{d^2}{D^2}\right)$$

where

d = Diameter of core
D = Diameter of bar

The results of Orowan *et al.*, together with those of the present work, suggest that this equation may apply generally to metals which have a relatively sharp yield point, in this case work-hardened copper and aluminium, and lead and steel, but not to work-hardenable metals such as annealed copper.



15—*Experimental bond strengths, plotted as a proportion of the strength of the solid metal, compared with the theoretical maximum attainable strength (full line)*

Reverting now to the consideration of a weld interface in which bonded and unbonded areas are interspersed, this can be regarded as a series of notched test pieces where the mean degree of restraint is given by the area joined per unit area, and this has already been shown to be equal to the reduction R. Thus

$$C=\frac{\text{U.T.S.}_c}{\text{U.T.S.}_t}=(2-R)$$

or

$$\text{U.T.S.}_c=(2-R)\,\text{U.T.S.}_t$$

so that the maximum strength of the weld (area bonded × bond strength) is given by

$$\text{U.T.S.}_{\text{weld}}=R\,(2-R)\,\text{U.T.S.}_{\text{solid}}$$

To obtain a comparison with the results of the bond strength measurements, it is necessary to assume that the relationship between the ultimate shear strength and the ultimate tensile strength is the same for both restrained and unrestrained metal. If this is so, then

$$\frac{\text{U.S.S.}_{\text{weld}}}{\text{U.S.S.}_{\text{solid}}}=R\,(2-R)$$

This theoretical curve is compared with the experimentally determined bond strengths, plotted as a proportion of the solid metal strength, in Fig. 15. It can be seen that the experimental values increase rapidly from the threshold deformation, and then follow the theoretical curve reasonably well.

The theoretical curve derived from this model therefore represents the maximum potential strength for oxidized metal, roll bonded, assuming that no bonding can occur between oxide films and that the oxide remains at the interface. Thus, for example, the curve would not be expected to apply to those cases of high-temperature welding where the oxide film can diffuse into the adjacent metal. It is particularly interesting to note that whilst the theory was derived on the basis of measurements made on the primary discontinuities in aluminium and copper, it agrees well with the bond strength determinations for lead and tin; in these the oxide fragmentation could not be observed, but it must therefore occur in much the same way as with the aluminium and copper.

The problem now remains of why this maximum strength is not attained until some deformation greater than the threshold value has been applied, and this involves a consideration of the reason for the existence of the threshold deformation itself and of the subsequent development of bonding. Unfortunately, no

positive contribution can be offered to the solution of this problem, although a number of significant factors have been investigated.

Initiation and Development of Bonding

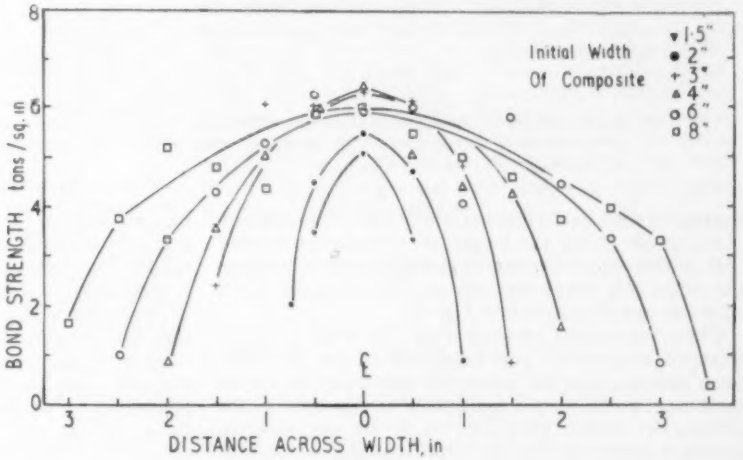
The approach to this aspect of the work has been to determine the effect on the bond strength of a number of factors generally known to be significant in welding, and which might moreover, clarify the mechanism of bonding. As before, bond strength measurements have been supplemented by a metallographic examination.

Rolling geometry

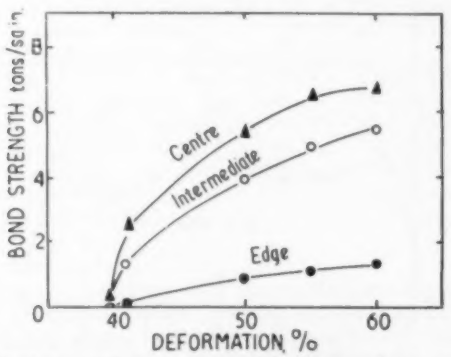
It is well known that the efficiency of pressure welding is dependent on the deformation pattern, and in the present series of papers Donelan[7] and Holmes[8] both stress the importance of the geometry of the deforming tool. In the present investigation, this factor was examined in so far as it arises in deforming metal by rolling; thus, the effect of specimen width, thickness, length, and roll diameter were investigated.

All the results so far reported were obtained from the central area of 4 in. square composites. A survey was now made of the strength across the width, for a number of different widths, of aluminium composites which had undergone 60% deformation, and the results are shown in Fig. 16. There is a marked falling off of the bond strength towards the edge of the composite, and as the width of the composite is increased the central strength increases to a maximum, after which it remains substantially constant. However, these results do not show how the bond strength developed with increasing deformation across the width of composites. In particular, it is not clear from them whether the initiation of bonding requires a greater reduction nearer the edge of the specimen, or alternatively, whether the same threshold deformation is necessary throughout but the bond strength develops less readily towards the edge. To examine this point the investigation was extended to further deformations and the results are given in Fig. 17. It can be seen that the threshold deformation is the same throughout, and it is the development of bonding which is pressure sensitive.

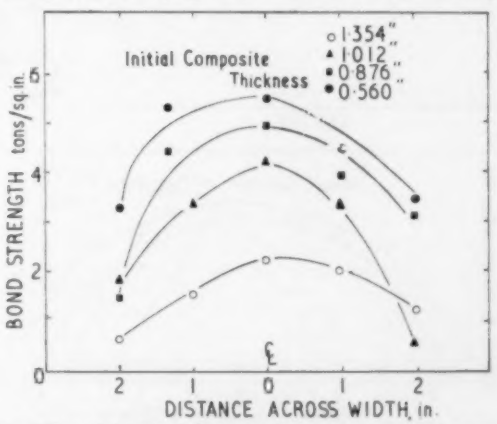
A similar investigation of the effect of varying the initial thickness of aluminium composites before rolling showed (Fig. 18) that the bond strength



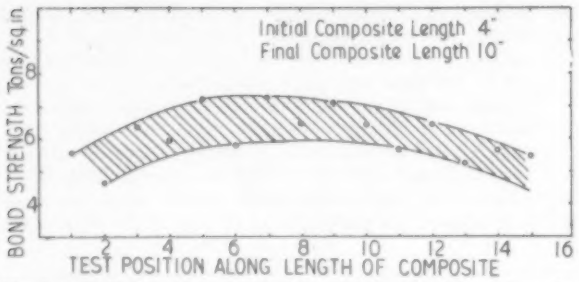
16—*Lateral variation in bond strength for aluminium composites, of various widths, which have undergone a 60% deformation*



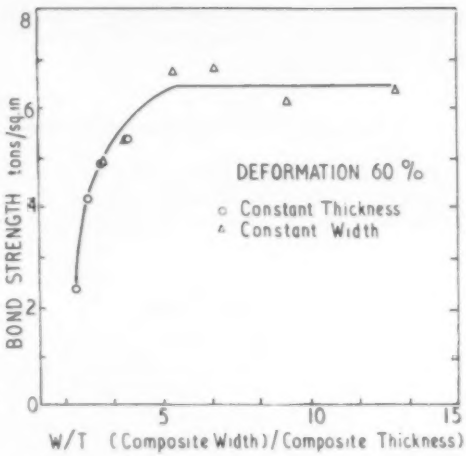
17—*Initiation and development of bond strength at various positions across 4 in. wide aluminium composites*



18—*Effect of the initial thickness of aluminium composites on the resulting bond strength (60% deformation)*



19—*Longitudinal variation of bond strength for aluminium composite (60% deformation)*

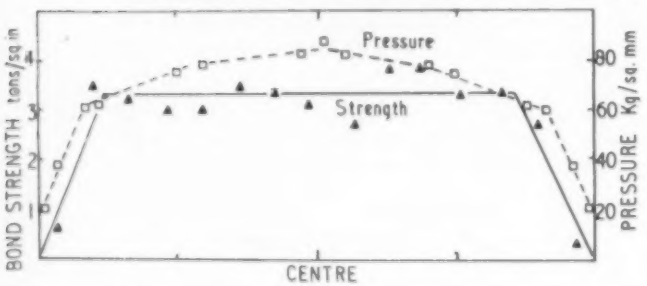


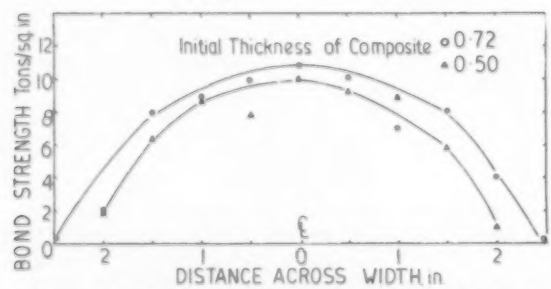
20—*Bond strength at the centre of aluminium composites, after 60% reduction, as a function of the ratio (composite width/composite thickness)*

decreased with increasing initial thickness. An examination made along the length of composites showed that, whilst some decrease in strength took place near the ends, this effect was not as marked as the effect of width and thickness (*see* Fig. 19).

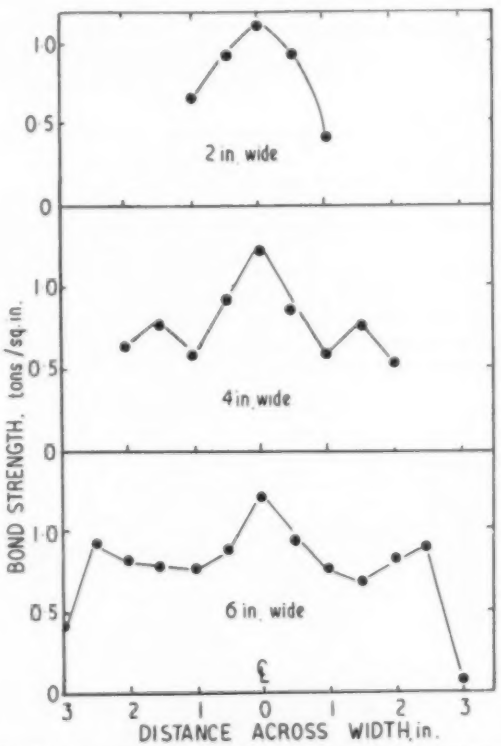
These variations showed that the weld strength changed appreciably independently of the deformation, and that another factor was therefore playing an important part. From a qualitative comparison of the parameters which were known to be operative in rolling it appeared that the bond strength varied with the pressure, but a quantitative comparison was difficult to make without embarking on a series of determinations of the pressure distribution in the roll gap, which is in itself a major problem. However, the comparison was pursued further in two respects. Firstly, when the strength at the centre of the aluminium composites was plotted as a function of the composite width/thickness ratio (using the results on the effect of both width and thickness, Figs. 16 and 18) it was found that the strength increased until the width/thickness ratio attained a value of about 6 (*see* Fig. 20) and thereafter the strength remained constant. It is well known that the mean specific roll pressure can behave in a similar manner, since the load required to reduce the metal has to be increased to overcome the

21—*Comparison between the pressure distribution across the roll gap as determined by Siebel and Leug[8] and the bond strengths obtained in the present work; reduction in both cases 47·5%*

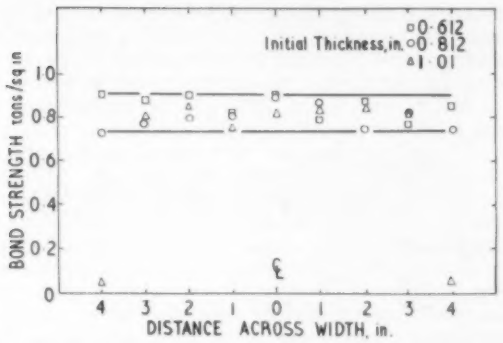




22—*Lateral variation of bond strength across 5 in. wide copper composites of two different initial thicknesses, reduction 60%*



23—*Lateral variation of bond strength across tin composites of different widths, reduction 50%*



24—*Bond strength surveys across the width for different thicknesses of 8 in. wide tin composites, reduction 50%*

frictional restraint exerted by the roll surfaces on the deforming metal. Secondly, the pressure distribution across the roll gap has been measured by Siebel and Leug[9] for aluminium strip measuring 30 mm. by 2 mm. and reduced by 47·5%, and whilst specimens of this size would not be satisfactory for bond strength determinations, it was possible to use a thicker composite having the same width/thickness ratio and compare the bond strengths with Siebel and Leug's pressures for the same deformation (*see* Fig. 21). It was found that increasing pressure up to 70 kg./sq.mm. increased the bond strength, but further increases in the pressure had no effect.

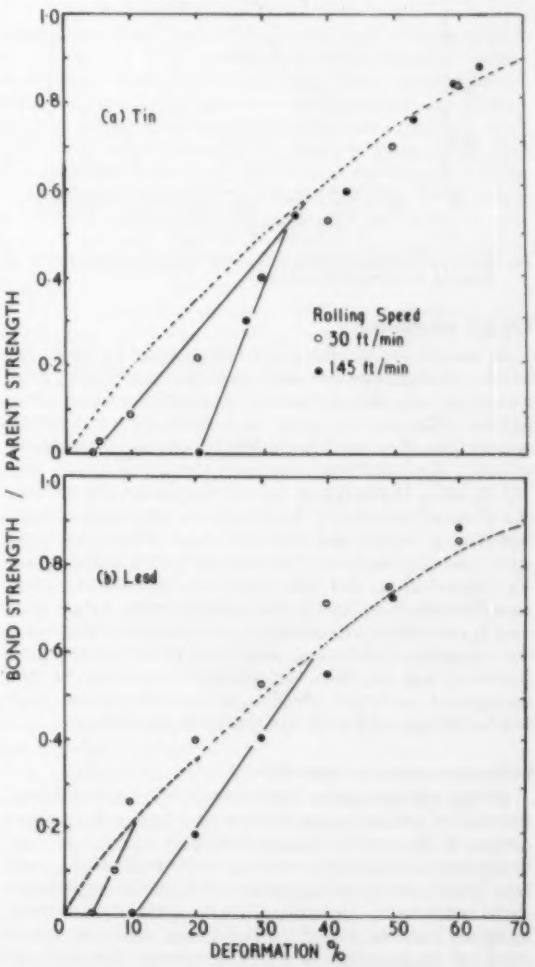
To determine whether these results were of a general nature or specific to the case of aluminium, lateral variations in bond strength were determined for several thicknesses of copper and tin. In the case of copper results similar to those for aluminium were obtained (Fig. 22). With tin, however, the situation was more complex; for a width of 2 in. the strength varied in a manner similar as with aluminium and copper, but as the width was increased to 4 in. and 6 in., subsidiary strength peaks appeared towards the edges of the composites (*see* Fig. 23). With a width of 8 in., the fluctuation in the bond strength had diminished to give an approximately uniform strength across the width, while changing the initial thickness had little effect (Fig. 24).

Thus, for aluminium and copper, pressure has a clear effect on the bond strength, but with tin, the complexity of the strength variation and the lack of data on pressure distribution in the roll gap make it impossible to arrive at a definite correlation.

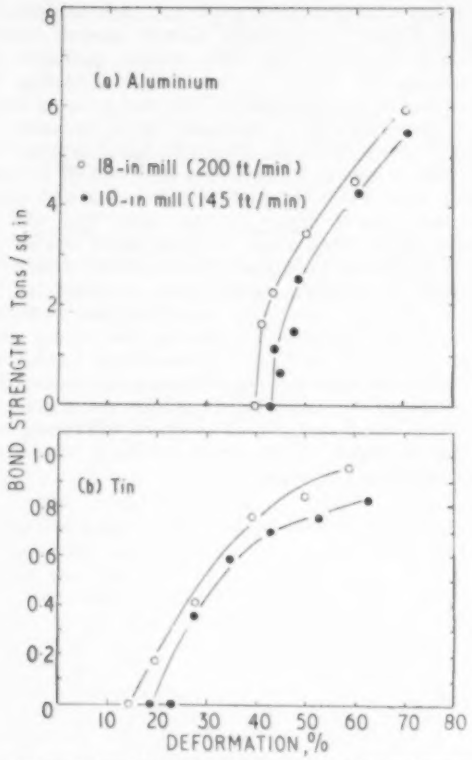
Owing to limitations in the control of speed of the rolling mills available, the effect of changing the geometry of rolling by changing the roll size could not be investigated without at the same time changing the rolling speed, and discussion of this aspect must therefore be left until the results on the effect of roll speed have been presented.

Effect of roll speed

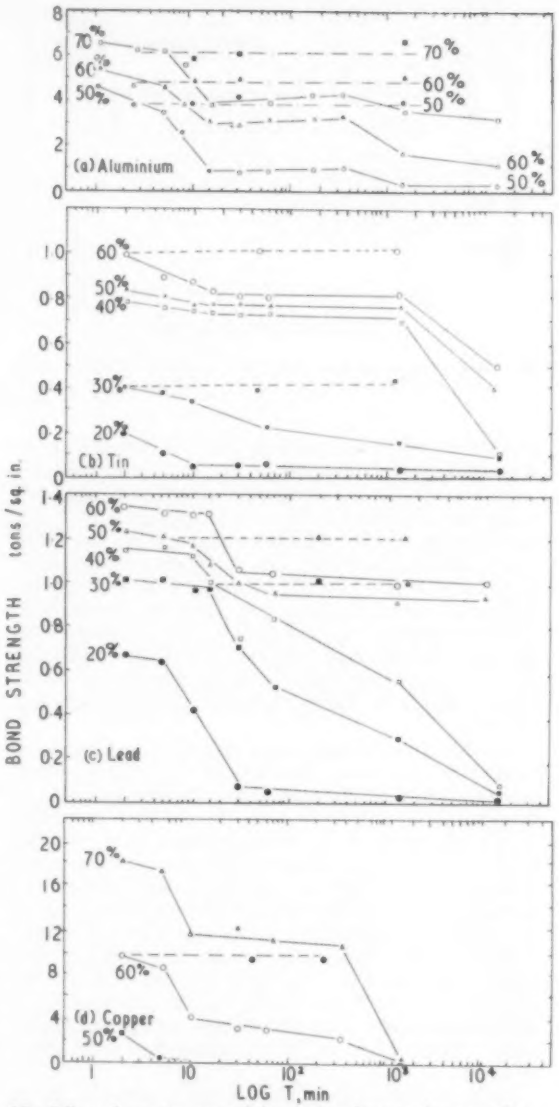
All results reported so far were obtained with an 18 in. rolling mill which operated at a fixed speed of 200 ft./min. But a knowledge of the effect of rolling speed is important, since if this parameter had any influence on bonding it would tend to support theories in which time-dependent processes such as diffusion played a part, and would militate against elastic-recovery theories. The only means available for examining the effect of time, while confining the investigation to roll bonding, has been to use a 10 in. two-high mill with a nominal speed variation of 0–145 ft./min. However, the lowest speed at which tin and lead could be fed into this mill was 30 ft./min., whilst with aluminium and copper such a high speed was necessary to obtain the necessary 'bite' that an insufficient working range of rolling speed was left for any investigation to be made. For tin and lead the bond strength deformation curves were obtained for the upper and lower limits of operating speed, and the results (Fig. 25) show that lowering the rolling speed from 145 to 30 ft./min. approximately halved the threshold deformation. No difference was observed in the shape of the strength/deformation curve once the maximum bond strength was attained, in keeping with the theory based on the oxide break-up model outlined earlier in this paper.



25—*Effect of rolling speed on initiation of bonding for* (a) *tin, and* (b) *lead. Broken line represents theoretical curve*



26—*Effect of changing rolling mill diameter on the development of bonding in aluminium and tin*



27—*Effect of exposing scratch-brushed surfaces to the atmosphere before rolling. Full line exposed to the atmosphere, broken line retained in a desiccator over P_2O_5*

Effect of roll diameter

In regard to the effect of rolling geometry in so far as the roll diameter has an influence, the difficulty here was that only two mills were available, which, while having different roll sizes, also operated at different speeds; the 18 in. mill had a fixed speed of 200 ft./min., whereas the maximum speed of the smaller mill was 145 ft./min. However, it has already been shown that the effect of decreasing the rolling speed was to initiate bonding at lower deformation; and when the bond strengths obtained with the two mills were compared it was found (Fig. 26) that the threshold deformation was decreased by using the higher speed, larger diameter, mill. Thus increasing the roll diameter promotes the initiation of bonding, and to a greater extent than shown by Fig. 26, since this should be modified to take account of the speed effect by an amount which could not be determined with the available equipment.

Influence of surface contamination

Of the many factors operative in pressure welding, the role of surface preparation and other surface parameters is the most obscure. Scratch-brushing combined with a degreasing treatment invariably gives the best bond strengths, and after some initial experience with machined, electro-polished, ground, emeried, scraped, and 'as-rolled' surfaces, the standard treatment of degreasing in trichlorethylene followed by scratch-brushing was adopted throughout. Even reversing the procedure, and degreasing after scratch-brushing, was found markedly to decrease the bond strengths obtained.

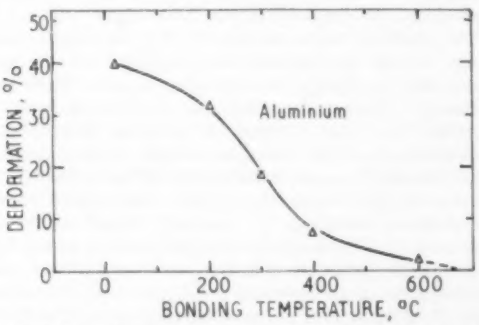
It is very difficult to make experiments on surface parameters in which a single factor is definitely isolated so that the results can be interpreted unambiguously. Researches on this aspect of pressure welding are now proceeding, but the results of a series of tests on the effect of atmospheric contamination, which appear to lead to a positive conclusion, will be presented here.

Composites of aluminium, copper, lead, and tin were rolled, following routine preparation except that after scratch-brushing the surfaces were exposed to the atmosphere for periods of from 2 min. to 10 days. The resulting bond strengths were found to fall into a

regular pattern (Fig. 27), declining markedly with exposure for the first 15 min., thereafter remaining constant for about a day; further exposure resulted in a steady decrease in strength, sometimes to zero, during the next 10 days. The reason for this was not immediately obvious. The thickness of the oxide film would not be expected to increase very much, for instance, in aluminium, where on scratch-brushing sufficient surface heating probably occurs for the very rapid formation of a film which would not be appreciably affected by further exposure at room temperature. Hence the alternative possibility, of the growth of layers of adsorbed material from the atmosphere, was investigated by repeating the experiments with the specimens held in a desiccator above phosphorus pentoxide. In every case the bond strength was found to remain constant. Thus, bonding is very much dependent on the presence of adsorbed layers, the main contaminant probably being water vapour.

Effect of temperature

It is well known that increasing the temperature can result in a very marked lowering of the deformation required for welding. This in turn must be pertinent to

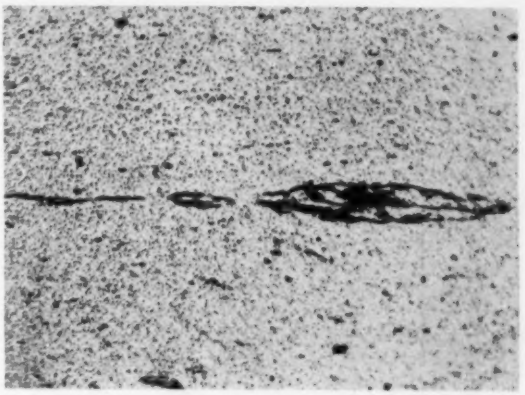


28—*Variation of threshold deformation with temperature for aluminium*

the mechanism of bonding, but so many factors and possibilities arise that again this is being treated as a subject for investigation on its own; only one result (Fig. 28) is presented here to show the magnitude of the effect of temperature on the threshold deformation for aluminium. At temperatures above 350°C. bonding was initiated with aluminium at a lower deformation than with lead at room temperature.

Correlation of the Initiation and Development of Bonding with Interfacial Characteristics

Earlier in this paper it was shown that the macroscopic measurements of bond strength could be correlated with the presence at the interface of primary discontinuities, and that the total length of these discontinuities was determined by the original length of the specimen. The theory was then proposed that the maximum strength was determined by the area of virgin metal which was available for bonding. Since this maximum strength is often not obtained, it might be expected that this would be reflected in the characteristics of the interface. Hence weld interfaces in

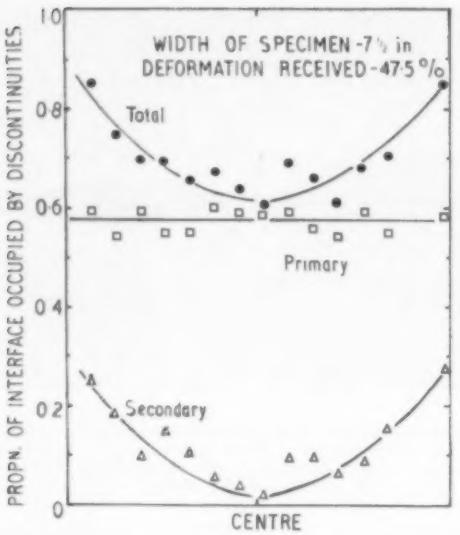


29—*Area of interface in aluminium with very little bonding, taken $\frac{1}{8}$ in. from the edge of an 8 in. wide composite. The secondary line discontinuity can be readily distinguished. Deformation 47%, ×250, etch 2% HF/27% HNO_3*

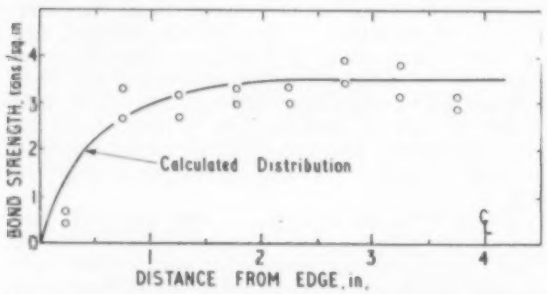
aluminium were examined for those conditions under which the maximum strength is not reached; composites were examined which had been subjected to deformations lying between the threshold value and that at which maximum strength was attained, and specimens were taken of interfaces away from the centre of the composite, and where surfaces had been exposed to the atmosphere before rolling. In all cases a further type of discontinuity, in addition to the normal primary types was observed, having the form of a hair-line crack; a typical example is shown in Fig. 29.

To correlate the presence of these secondary discontinuities with the observed bond strength, a survey was made of their distribution for various cases, and the strength was then calculated by taking account of the triaxial stress conditions as described on p. 20. It will be appreciated, from a comparison of Fig. 29 with Fig. 6*a*, taken at the centre of a composite and showing only primary discontinuities, that the length of a secondary discontinuity was much more difficult to define accurately, so that there was more scatter with these results. Nevertheless, the correlation was clear enough; Fig. 30 shows the result of such a survey, and the corresponding calculation for the lateral variation in bond strength of aluminium reduced by 47% is given in Fig. 31, which also shows the experimental bond strengths. The distribution of the primary discontinuities always conformed to that expected from the concept of two scratch-brushed layers breaking up as one, as had previously been found for the centre of the standard composites.

A similar examination, although not so extensive, was also made for copper, but in this case the metallographic technique appeared to play a more important part, as a series of discontinuity types could be seen. These varied from the hair-line crack representative of aluminium, through degrees of width, to the relatively thick primary type, so that no clear distinctions could be drawn. With tin and lead, no technique has been found which can resolve the fine structure of the continuous boundaries to show how the interfacial characteristics vary with the joint strength.



30—*Distribution of primary and secondary discontinuities across the width of an aluminium composite*



31—*Lateral variation of bond strength determined experimentally, compared with that calculated from the distribution of primary and secondary discontinuities (full line), for the aluminium specimen corresponding to Fig. 30*

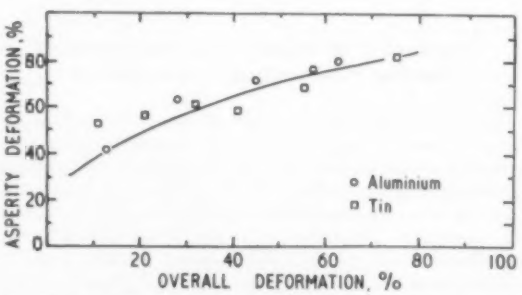
Discussion

The purpose of these researches has been to investigate the mechanism of pressure welding in the roll bonding process, and while a body of data has been obtained which provides a basis for analysis, shows the relationship between a number of variables, and allows partial conclusions to be drawn, no overall theory can be offered. However, the research is continuing into some of the more critical aspects, and it is hoped that the information gained will lead to further developments. In the meantime it is possible to arrive at some conclusions regarding the correct model which has to be pursued.

Taking first a broad view, two possibilities exist: either welds do not readily form, or alternatively they do form, but are broken apart by elastic recovery forces, as was suggested by McFarlane and Tabor.[10] There are two arguments against elastic recovery playing a major part. Firstly, it is difficult to visualize how such forces could be effective when two virtually flat blocks are rolled together, as opposed, for example, to the case of a hard spherical indentor pressing into a flat surface, for which this model was originally developed. Secondly, there is the fact that the initiation of bonding shows a marked time dependence, which would be difficult to explain on an elastic recovery model. Thus, it would appear that it is the factors that are operative in causing the surfaces to come into intimate contact which are important, and if this problem is considered at a macroscopic level, these are the presence of an oxide film and the difficulty of bringing two rough surfaces into contact.

On the basis of the results presented in this paper, it has been possible to define the role of the oxide film which is initially present on the metal surface, as preventing bonding over the area which it occupies, this area being equal to the initial area of the composite. This model differs from that previously postulated for the behaviour of the oxide film by Tylecote,[11] who suggested that it was the ratio of the hardness of the oxide film to that of the underlying metal which determined the degree of fragmentation of the oxide film, and that this in turn controlled the initiation of bonding. By contrast, the present work leads to the conclusion that the break-up of the oxide film determines the maximum bond strength attainable, but that other factors control the initiation of bonding.

The problem now remains of why the virgin metal areas, created by the extension in length of the composite during rolling, do not always weld. Pugh and Holmes[3,8] have recognized that contact across the interface may be difficult to achieve, because the restraint imposed by the adjacent bulk metal may make asperities on the surface difficult to deform. In order to determine how much this factor contributes to the difficulty of bringing two surfaces together, the extreme case, of the deformation of a surface into which a series of deep grooves had been machined, was investigated in the present work. Lateral **V** grooves 0·05 in. deep and separated by distances of 0·25 in. were milled out of the surfaces of tin and aluminium plates, 4×4×0·3 in., which were then clamped onto polished plates of the same material. A series of these composites was rolled, using the 18 in. dia. mill, and the deformation of the grooves was compared with the overall deformation. The immediate observation was that at reductions as low as 5%, when the grooved surface had apparently deformed very little, the surface that had originally been flat had become a complete replica of the grooved surface, even to the extent of



32—*Comparison between the deformation of macroscopic asperities and the overall deformation, of grooved aluminium and tin plates rolled against flat plates of the same material*

reproducing the marks of the machine tool. However, when detailed measurements were made (*see* Fig. 32) it was found that at low deformation the height of the surface asperities had undergone more than the mean reduction. Even so, no flattening of the tips of the asperities could be observed. Thus it is clear that there should be no difficulty in bringing two surfaces into macroscopic contact, even when they are both rough, as at any position across the interface the degree of roughness, and hence the flow stress, will be less at one surface than the other, so the rougher surface will penetrate the smoother to cause overall intimate contact.

Macroscopic contact of the virgin metal areas should therefore be readily obtained, but this is not sufficient for bonding, which will occur only if the surfaces are brought into contact within atomic dimensions, so that the attractive forces between atoms can operate. It is the analysis of how this occurs, at a level in which atomic movements are considered, that constitutes the problem of the mechanism of bonding; this problem of the formation of welds in the solid phase is not specific to pressure welding, but is also relevant to sintering and frictional phenomena. Various considerations are involved; first, there is the flow of the metal, which takes place by slip and other more complex movements of dislocations and vacancies along favoured atomic planes. But it is not possible to bring two surfaces into intimate contact by processes which occur along crystallographic planes which are even only a few atomic distances apart, so that, as well as mechanical flow, local readjustments by diffusion processes in the vicinity of the interface must be essential. Also, unless the welding operation is carried out under a very high vacuum, there is the problem of the solution of the entrapped gases to be considered. Fine, Maak, and Ozanich[12] have shown by special etching techniques that with steels the layer of metal adjacent to the interface is oxygen-rich when welds are made in air, and the present work has shown that adsorbed water vapour can have a particularly deleterious effect. Thus, at a deformation of 60% all the virgin metal area was found to weld if the composite was rolled within two minutes of scratch-brushing, but if water vapour became adsorbed on the surface it did not remain attached to the oxide, but was sufficiently 'mobile' to contaminate some of the virgin metal areas as they formed and thus reduce the bond strength. Held and Hendus,[13] by carrying out their experiments in a 'high' vacuum (using a diffusion pump), eliminated as far as possible the influence of these adsorbed and entrapped gases (although possibly also removing the oxide film), and were able to initiate the bonding of Armco iron with negligible deformation by holding for one hour at 400°C., most unusually favourable conditions for iron.

Since mechanical deformation, atomic readjustment at the interface, and the solution of entrapped gases are all to some extent dependent upon diffusion phenomena, the influence of time and temperature is obvious. Conversely, varying the time or temperature could change any or all of these processes so that, without further control, experiments investigating these parameters yield ambiguous results. It is difficult to isolate the individual processes which can operate in bond formation. Thus, for example, Erdmann-Jesnitzer and May[14] virtually eliminated deformation and drastically reduced the applied load in a series of experiments to determine the temperature at which welding was initiated between copper rods abutted under a light load and heated in a protective atmosphere, and found that bonding occurred at 740°C.; a similar series of experiments was carried out by Parks[15] for a number of metals, but although the conclusion was that welding begins in the region of the recrystallization temperature, it is difficult to relate these results to the mechanism of bond formation in welding as it is normally practiced. Cook and Davis,[16] approaching the problem from the purely practical viewpoint of determining the optimum conditions for the welding of high-conductivity copper, found that the U.T.S. of a butt-welded joint made in 10 min. at a temperature of 500°C. and pressure of 1·5 tons/sq.in. was 8 tons/sq.in., but that if the pressure and temperature were maintained the strength increased, until after 30 hr. it had almost doubled, to 15·5 tons/sq.in., thus demonstrating most strikingly the general influence of these factors.

The remaining parameter which this work has shown to be of significance is pressure. Other workers have also found pressure to have an effect; Hoffman and Ruge[17] in particular related welding to pressure, but these workers, having found that there was a critical pressure at which marked flow of the metal readily took place, concluded that it was in fact the flow of the metal that was significant, and the pressure only of importance in that it brought this flow about. In the present work the influence of pressure was demonstrated *via* changes in the geometry of rolling—in particular, the bond strength varied markedly across the width; but since the metal flow had been substantially the same throughout the composite, there is no correlation with the work of Hoffman and Ruge. If in fact the enhanced metal flow were the critical factor, the stronger bonds would be expected at the edge of the specimen where some lateral spread occurred, whereas the bond strength in this region was very low. Whether increasing the applied pressure affects the atomic processes of mechanical deformation is not known, and since it could have an effect on the diffusion of metal atoms, of vacancies, and of entrapped gas in the metal, the exact role of this variable is particularly difficult to evaluate.

The most positive aspect of this work is the role it assigns to the oxide film, and it would be very useful if the concepts involved could be applied to the other pressure welding techniques. This, however, would require a knowledge of the relation between the deformation of the metal and the increase in area of the interface, and this is not known either in small-tool or in butt welding. However, one piece of work does have some relevance; Austin and Jeffries[18] in 1932 carried out butt welding of various types of steel at high temperatures, and measured bond strengths and examined interfaces. As in the present work, they observed discontinuities at the interface, which they regarded as patches of oxide. By some unspecified means these workers determined the apparently bonded area, tried to correlate it with the bond strength, and found that higher strengths were obtained than would be expected on a basis of the weld strength being equal to the apparently bonded area multiplied by the strength of the metal as determined by normal

tensile tests. For this reason, Austin and Jeffries concluded that there must be some bonding between oxide and metal. However, when the concept of restraint, and the relation between the degree of restraint and constraint factor, is applied to these results as described on p. 20, it is found (Table II) that on recalculation there is very good agreement between the measured bond strengths and those calculated from the weld area measurements.

Table II

Relation between bond strengths of butt-welded steels and values calculated from weld areas

Experimental Results of Austin and Jeffries[18]

Type of steel	*Weld area, %*	*Metal strength attained by welding, %*	
		Experimentally Determined	*Calculated*
Open Hearth	55	80	80
Open Hearth	50	75	75
Open Hearth	80	105	96
Open Hearth	60	85	84
Bessemer	70	97	91
Bessemer	50	80	75
Bessemer	60	85	84
Bessemer	60	80	84

In summary, an assessment of the available information on pressure welding leads to the conclusion that the initiation and development of bonding are complex phenomena, depending on a variety of factors, but that the maximum bond strength attainable, at room temperature at least, is determined by simple geometrical considerations.

Conclusions

Practical application of cold roll bonding

(1) For room temperature welding, a deformation of 60–70% is required with aluminium, copper, lead, tin, and zinc to obtain weld strengths equivalent to those of solid metal.

(2) The first roll pass should be sufficient to cause the composite to adhere; thereafter the weld strength can be built up by successive small reductions.

(3) Weld strengths deteriorate rapidly as water vapour is adsorbed on the faying surfaces.

(4) Bonding is promoted by the use of low rolling speeds and large-diameter rolls.

(5) With the harder metals investigated (aluminium and copper), the bond strength is low for a region of about 1 in. from the edge of the composite.

The fundamentals of pressure welding relevant to roll bonding

(1) The maximum bond strength that can be achieved at room temperature can be calculated on the assumption that there are present on the surface of the composite brittle oxide films which come together at an early stage of their progress through the roll gap and thereafter behave as one. These films are completely brittle, so that the virgin metal area which is potentially available is the increase in area of the interface. Taking account of the triaxial stress conditions existent when a load is applied, the maximum ultimate shear strength that the weld can have, if the whole of the virgin metal area bonds is given by:

$$\text{U.S.S.}_{\text{weld}} = R(2-R)\,\text{U.S.S.}_{\text{solid metal}}$$

where R is the reduction. (This result would not apply to high-temperature welding where the oxide film can diffuse into the adjacent metal.)

(2) In many cases, no bonding, or less than the maximum strength, is obtained; this is due to the difficulty of bringing two surfaces into atomic contact, and the correct model for the mechanism of the process will have to take into consideration mechanical flow of metal in terms of atomic movements, local readjustment at the interface by diffusion, and the solution of entrapped gases.

Acknowledgments

This work is part of a programme of research into some aspects of the joining of metals, which is being carried out at the Department of Industrial Metallurgy at the University of Birmingham. The authors wish to thank Professor E. C. Rollason, Head of the Department, for his interest and encouragement throughout the course of this work, and the Director of the United Kingdom Atomic Energy Authority at Harwell for financial support for two of them.

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INFLUENCE OF RELATIVE INTERFACIAL MOVEMENT AND FRICTIONAL RESTRAINT IN COLD PRESSURE WELDING

By E. Holmes, M.A., PH.D.

Relative movement of overlapped strips under compression by tools of narrow annular cross-section, and the oxide dispersal attendant upon this movement, permitted some permanent bonding to occur between aluminium or copper autogenous assemblies, but did not aid the attainment of maximum joint strength by subsequent direct indentation. The initiation of welding in similar assemblies when indented by small-diameter tools was made to occur at a lower deformation when an increased frictional restraint was imposed from a larger tool face at some intermediate stage of the operation. From the observation of anodized films, it was anticipated that increased restraint retarded oxide break-up, and it was shown that continued indentation from the larger faces did not permit the attainment of full bond strength. It is suggested that, for these assemblies, the removal of interfacial voids mainly determines weldability when using tools of small cross-section, but that oxide dispersal becomes more important as the tool size increases.

The strengths of welds made between aluminium and copper were solely dependent upon the deformation of the copper component, and were increased by preliminary sliding at the interface. Oxide on the copper members was considered to be the final barrier to cold welding of this type of assembly.

Introduction

SCIENTIFIC interest in the ancient art of pressure welding may be said to date from 1724, when Rev. J. T. Desaguliers[1] drew the attention of the Royal Society to experiments indicating the ease with which lead could be joined manually at room temperature by a simultaneous pressing and twisting operation. In more recent years, the significance of a twisting action has not been stressed, except in a paper by Cooke and Levy[2] concerned with the welding of aluminium to steel at elevated temperatures. However, when interest in cold welding was renewed by Sowter,[3] it was at first* reported that overlapped strips of lead required considerable indentation to weld them, this being ascribed by Tylecote[4] to the difficulty of dispersing oxide films from the interface. Oxide dispersal by interfacial sliding has been demonstrated in friction experiments described by Bowden and Tabor,[5] and consideration was therefore given in the present work to the possibility of facilitating cold welding by relative movement of the surfaces to be joined.

It was appreciated, however, that oxide dispersal was not the only prerequisite for good bonding, since the forces of interatomic attraction, upon which weld cohesion depends, can become significant only when the metallic atoms of the members to be joined are not separated across the interface by more than a few atomic spacings. This requires that the initially unmatched surface contours must be modified as a result of the applied pressure, a condition which was regarded by Pugh[6] in his cold welding experiments as being more important than oxide dispersal. It was considered that the removal of interfacial voids would be facilitated if, by the application of a side restraint, the stress across the interface could be increased. In the present experiments, variation in side restraint was provided by the simple expedient of altering the cross-section of the indenting tools, and thereby changing the frictional forces that they imposed.

A third factor, which has been considered as a criterion for pressure weldability by McFarlane and Tabor[7] and by Udin, Funk, and Wulff,[8] namely the extent to which a joint may suffer partial or complete failure as a result of the redistribution of elastic stresses during the release of the welding load, was not directly investigated during the present survey. It was, however, considered that this factor should be most significant for low-ductility bonds, and should militate against the use of side restraint because of the increased elastic stresses thereby imposed.

Experimental Details

Previous workers have indicated that the strengths of cold pressure welds are influenced by variations in technique, such as the method of cleaning and the speed of welding; thus, the procedure adopted in the present work was standardized in the following manner. Strips to be joined, 6 in. long, 1 in. wide and 0·048 in. thick, were first degreased using trichlorethylene vapour degreasing equipment. Solid impurities were then removed from the surfaces to be joined, using a coarse, mechanically operated wire brush; this

* Later workers, including Pugh,[6] have attributed better cold welding properties to the soft metals, lead and tin, than did Sowter or Tylecote.

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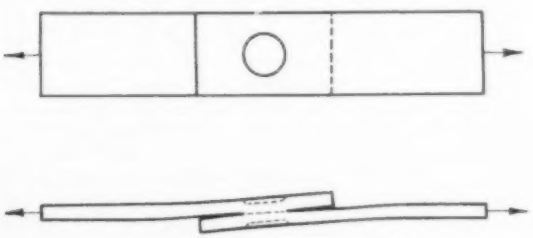
method was chosen to minimize further contamination, such as that produced by chemical reaction during pickling or by physical embedment during emery abrasion. Reintroduction of grease at this stage was prevented by degreasing the brush used and by refraining from handling the areas to be joined. The strips were overlapped approximately 1½ in. and, within one minute of cleaning, were welded by indentation, the shape and size of the tools used depending on the experimental requirements.

1—*Tools and holder for welding with relative movement at strip interface*

In the apparatus used for welding by relative movement of the strip surfaces (Fig. 1), the tool guides were designed to permit rotation with respect to one another, movement under load being facilitated by two sets of thrust bearings. The strips to be joined, held one to each guide in 1 in. wide grooves, were made to slide one over the other as a result of the rotation. Tools of annular cross-section, having internal and external diameters of 0·470 in. and 0·548 in., respectively, were used, their circular section allowing the same area of strip to remain between the tools during the operation, whilst their narrow form ensured that the sliding movement was approximately uniform over the whole weld area. At the beginning of each test, the strips were placed in position in their respective grooves and set at a known angle out of alignment. A predetermined load was then imposed through the tools and, by rotation of the upper tool holder, the strips were brought into line. During this operation the load imposed changed slightly, in general decreasing but occasionally increasing when light loads were used. It was impracticable to adjust the load during sliding to compensate for this small change but, as it was no more than 5%, it should not materially have influenced the validity of the results. The breaking load for some of the joints was determined after the completion of sliding, but most specimens were tested after an increased load had been applied to the tools, to indent the strips further. One of each pair of strips had to be bent before welding to fit into its groove. It was re-straightened with a slight load imposed through the tools onto the completed weld; this load was necessary to prevent fracture of low-strength



2—*Method of testing pressure welds*

bonds, but was unimportant for straightening strong joints.

When no relative movement of the strips was needed, a simple cylindrically shaped tool guide was used, in which the strips to be joined were accommodated inside a radial slot, without bending. Most of these tests were made to determine the influence on welding characteristics of the different amounts of frictional restraint on the strip produced by indenting tools with one of the following cross-sectional dimensions:

(*a*) Annular tools, internal and external diameters 0·470 in. and 0·548 in., as used in rotation welding
(*b*) Large-diameter tools, 0·625 in. dia.

(*c*) Small-diameter tools, 0·200 in. dia.

(*d*) Stepped tools, 0·625 in. overall dia. reduced coaxially to 0·200 in. at the indenting surface for a short distance referred to as the step height.

The strength of each joint was determined by pulling the straightened strips apart in a tensile testing machine (*see* Fig. 2). The stress distribution at the time of fracture was complex but, within the limits permitted by variations of weld deformation and shape, the tests were comparable one with another.

The breaking loads so obtained were related to deformation at the indentation, defined as:

$$\frac{\text{Change in thickness}}{\text{Initial thickness}} \times 100\%$$

The thickness considered was the combined value for the two overlapped strips, except when the deformation of a single component is specifically mentioned.

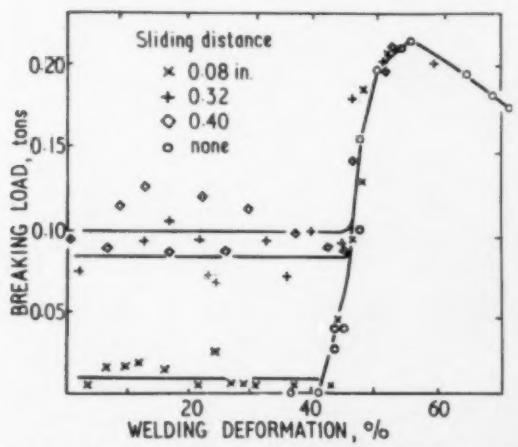
Autogenous Welds

Bonding assisted by sliding

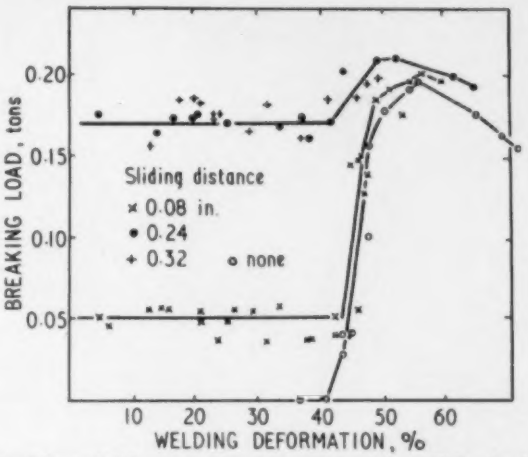
Autogenous welds were made in aluminium and in copper, using several combinations of sliding load and distance within the limits permitted by the apparatus and the operation. Thus, the maximum circular movement in one direction, measured in terms of the mean tool diameter, was limited by the design of the apparatus to 0·4 in. The maximum load was limited to 0·3 tons for aluminium and 0·7 tons for copper; for greater loads, the strips tended to force their way out of the retaining grooves rather than to rotate with them.

Reduction in strip thickness imposed by the relative movement was rarely more than 2%, but the operation was sufficient in most instances to produce some permanent bonding. The use of larger loads or sliding distances, within the limits permitted by the experiment, improved the joint strength, but each successive increase had a proportionately smaller influence.

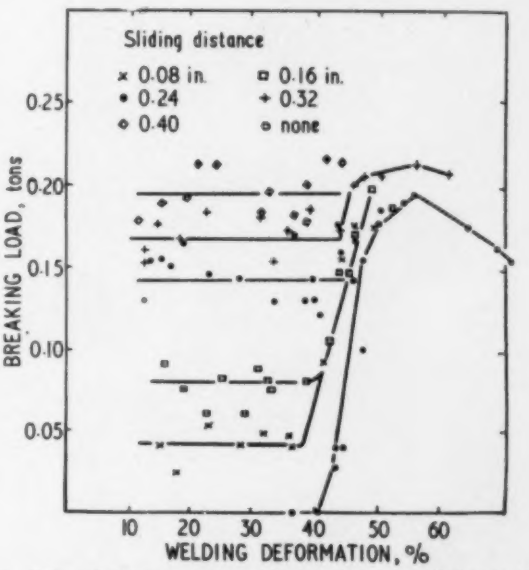
These results were in qualitative agreement with Orowan's experiments on friction between annular aluminium specimens,[9] in which he found that the coefficient of friction increased with sliding distance,



3—*Effect of sliding on cold welding of aluminium: Sliding load 0·1 tons*



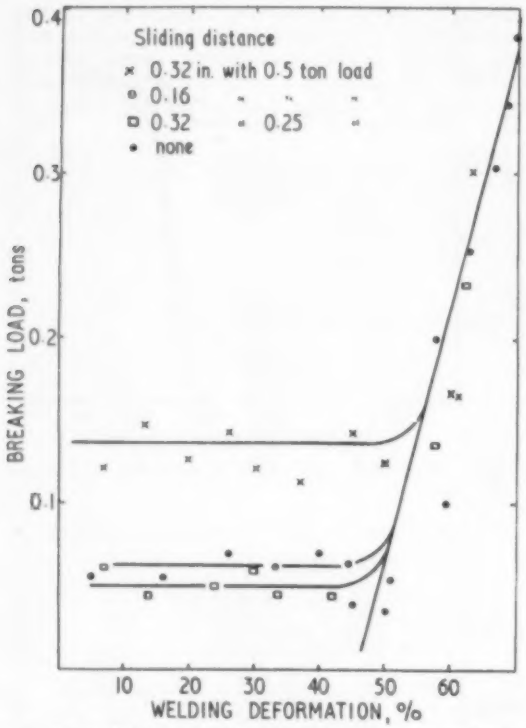
4—*Effect of sliding on cold welding of aluminium: Sliding load 0·2 tons*



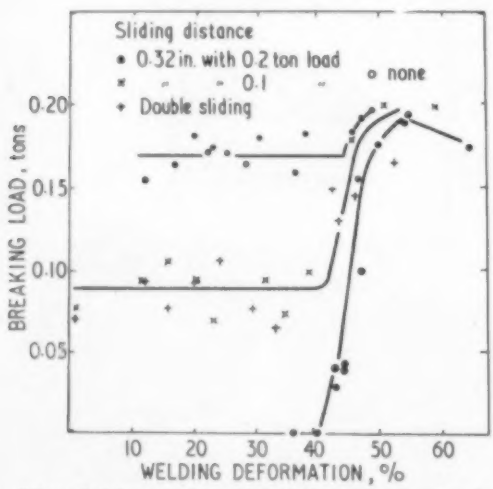
5—*Effect of sliding on cold welding of aluminium: Sliding load 0·3 tons*

the change being significant at first but negligible after 2 mm (0·08 in.) of movement. Both sets of results show that oxide dispersal from earlier stages of the sliding action is still effective in the later stages. The conclusion of Bowden *et al.*,[5] that friction was unaffected by sliding distance, applied to different conditions in which sliding was not confined to the same area of material throughout; this finding is therefore not in conflict with the present experiments.

The breaking loads of joints which were subjected to a further deformation without sliding have been related to the total deformation imposed; the results for aluminium are given in Figs. 3–5, and those for copper in Fig. 6. For similar conditions of initial sliding, the variations in breaking load were not significant if the total deformations were below 40% for



6—Effect of sliding on cold welding of copper at various loads



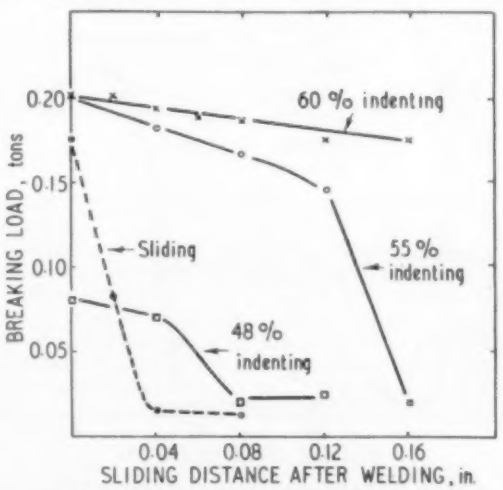
7—Effect of sliding on cold welding of aluminium at various loads

aluminium and 50% for copper; these are the deformations required to initiate bonding in the absence of sliding. Differences which did exist were in the nature of a random scatter totally unrelated to welding deformation; thus, in the diagrams, a mean horizontal line has been drawn through each series of representative points. At higher deformations the breaking load increased to a value equal to, or very slightly greater than, the maximum obtainable without any sliding action.

It may thus be concluded that sliding, despite its accompanying oxide dispersal, did not significantly assist the autogenous welding of copper or aluminium by subsequent static loading between annular tools; this implies that oxide dispersal is not the difficult part of this form of pressure welding. Further evidence in support of this conclusion was obtained by submitting strips of aluminium to a double sliding action, in which a movement of 0·32 in. under a load of 0·2 tons was followed by an equivalent movement under a load of 0·1 tons. The resulting breaking loads for these welds were similar to those obtained by a single sliding action at the lighter load (*see* Fig. 7). The stronger bonds expected from sliding under the heavier load must have fractured at least in part during the second sliding action, although the extensive oxide break-up required for high bond strength should have been retained. Despite this, subsequent static loading did not cause satisfactory bridging until the deformation was sufficient to have caused bonding without sliding.

Bond failure due to sliding

Joints in aluminium made by sliding, and others made by direct pressing, were compared in their ability to withstand further sliding movement under light loads without fracturing. The nature of the experiment did not allow the measurement of joint strengths before the final sliding action, but these could be assessed from previous tests. Most of the joints were chosen so as to have an estimated breaking load of about 0·2 tons, since this value, near the maximum attainable, was more consistently reproduced than any other. After these welds had each been twisted under a load of 0·1 tons for a predetermined distance, the strips were removed from the tool-holder and tested in the usual manner. The results, shown in Fig. 8, indicate that only those bonds which were made by static loading, and were of high strength, were capable of withstanding large amounts of sliding without failure.



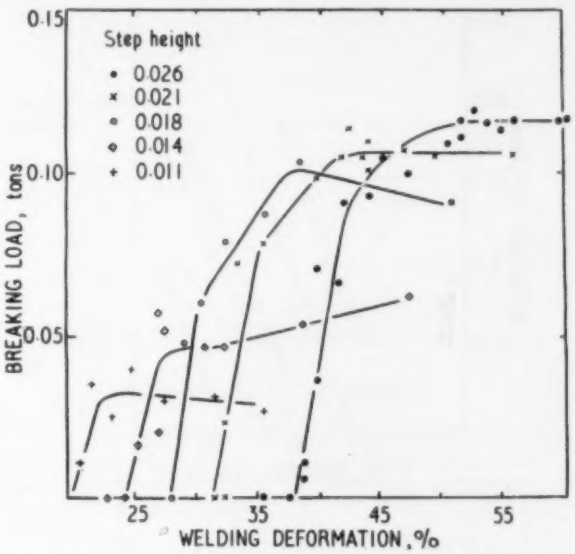
8—Effect on bond strength of sliding after welding

Variation of frictional restraint

In preliminary tests on welding without sliding, using strips of 0·048 in. annealed aluminium, quite different pressure welding characteristics were obtained with 0·200 in. dia. and with 0·625 in. dia. indentation tools. For the smaller tools, the general shape of the curves relating welding deformation to the resultant bond strength was analogous to that obtained for annular tools; a deformation of about 40% was necessary to induce slight permanent bonding, whilst an additional 15% was sufficient to produce joints having a maximum breaking load of 0·12 tons. In contrast, with the 0·625 in. dia. tools, a deformation of 75% was required to produce joints of 0·12 tons breaking load, although the indenting surfaces had approximately ten times the area of the smaller tools. Using the larger indenters, however, it was possible to induce very slight adhesion with only 2% deformation; this effect was not noticed when using 0·200 in. dia. tools, and was no doubt caused by mechanical interlocking of the surface asperities. This seems to confirm the belief that higher frictional restraint from the larger-diameter tool assists the modification of the surface asperities. The poor bonding induced by the larger tools was considered to be due to the difficulty of oxide dispersal, which appears to be more easily accomplished with smaller tools.

The possibility that increased oxide dispersal from the smaller-diameter tools might be combined with the desirable effects of the larger tools was studied by indenting with tools made up of two concentric steps, the face making the initial indentation being of 0·200 in. dia., which increased sharply to 0·625 in. dia. Several series of tests were made, the step height being changed for each series.

The results of these experiments are shown in Fig. 9. An improvement in weld strength was obtained by indenting with tools of greater step height, but the deformation required to initiate bonding decreased with a reduction in the size of the step. For tools having a small step height, this onset of welding coincided approximately with the occurrence of some permanent marking of the strips by the larger, 0·625 in dia., tool faces. However, at the onset of welding, the separation of these larger faces was greater than the combined thickness of the overlapped strips; thus, the nominal area of contact between the prepared surfaces of the strips was confined to that of the smaller-diameter portion of the tool. It follows that the initiation of welding for each step height occurred under almost identical flow conditions, since the greater part of each indentation was produced by tools of identical shape, and negligible flow had resulted from indentation by the larger-diameter faces. The results would suggest that oxide dispersal from the initial indentation by the smaller tool was sufficient to produce bond strengths in excess of those actually obtained, the full effects of this dispersal appearing only when adequate asperity deformation was induced as a result of some frictional restraint from the larger-diameter faces. Once these faces exerted their full restraining influence, further indentation caused little if any increase in joint strength. On the basis of these conclusions, the stepped tools might be used to obtain an indication of the extent of oxide dispersal produced by the smaller tools before the larger faces began to make their impression.



9—Cold welding of aluminium with step-shaped tools

Aluminium to Copper Welds

Variation of frictional restraint

In all the joints made between copper and aluminium, the copper was in the annealed state, and the aluminium was used in either the annealed or in the heavily cold-worked condition. Overlapped strips of the two metals were indented with differently shaped tools, one of circular cross-section, 0·625 in. dia., and the other of annular cross-section, having 0·470 in. internal and 0·548 in. external diameter. The former tool, having a larger area of contact, provided more restraint than the latter, and was used in turn on the soft and hard side of the combination. In addition, welds were made with an annular tool on each side of the overlapped assembly.

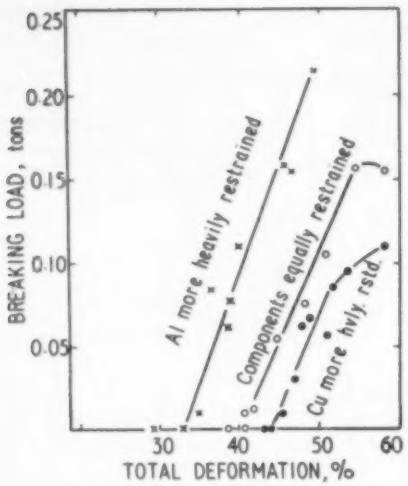
Strengths for the three forms of restraint are related to the total deformation and to the deformation of the copper component in Figs. 10–13. Two important conclusions emerged from this part of the work:

(*a*) Bond strengths were determined by the deformation of the copper component, regardless of the tool arrangement and therefore the relative restraint of the components

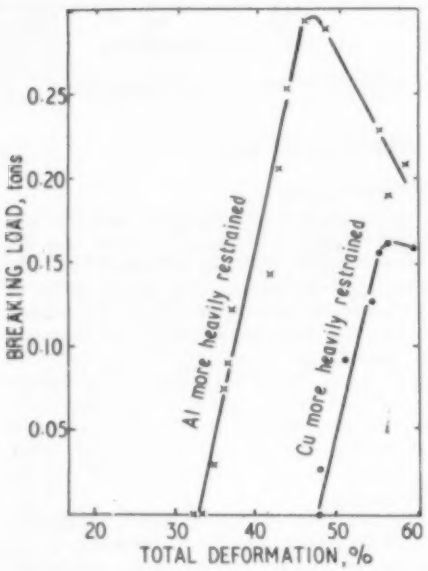
(*b*) Considerably smaller deformations of the copper were required to bond copper to aluminium than were needed to join copper to copper.

The first of these conclusions would suggest that some condition of the copper component, probably oxide dispersal, was limiting the extent of bonding between aluminium and copper. The other requirement, increased interfacial contact, should be determined primarily by the easier flow of the asperities on the softer of the two metals, and would almost certainly have been dependent upon the deformation of the aluminium. If this is so, asperity deformation was not controlling the extent of welding for this particular metal combination.

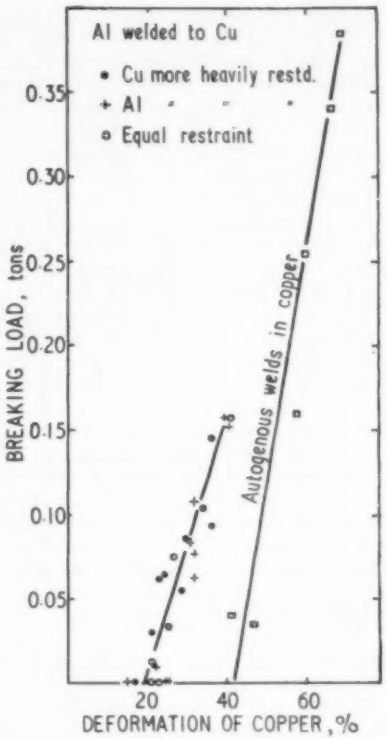
The second conclusion would suggest either that



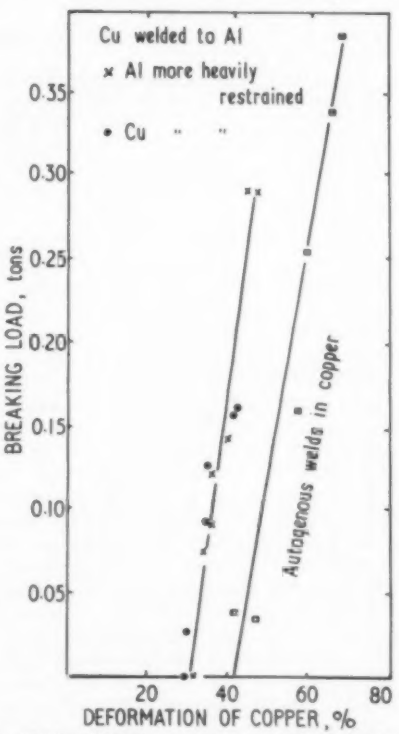
10—*Cold welding of copper to annealed aluminium*



12—*Cold welding of copper to pre-strained aluminium (D.P.N. 51)*



11—*Cold welding of copper to annealed aluminium compared with autogenous welding of copper*



13—*Cold welding of copper to pre-strained aluminium (D.P.N. 51) compared with autogenous welding of copper*

oxide dispersal was more difficult to achieve in autogenous than in the duplex welds or, alternatively, that in the autogenous welds adequate oxide dispersal occurred well in advance of permanent bonding. The large difference in bonding deformations required in the two cases would lend support to the latter alternative, and thereby to the suggestion already made, that restricted asperity deformation may be the ultimate limitation on permanent bonding in autogenous copper assemblies.

Bonding assisted by sliding

Bonding of copper to aluminium differed in another respect from the autogenous welding already considered, in that relative movement between the dissimilar metal surfaces was able to reduce considerably the deformation required to obtain full bond strength by subsequent static loading. The results in Fig. 14 show that, if sliding loads and distances are themselves sufficient to effect some permanent bonding, they enable full bond strength to be obtained during subsequent static loading for a total deformation as small as 30%. This deformation did not produce even slight permanent bonding if the sliding action was omitted.

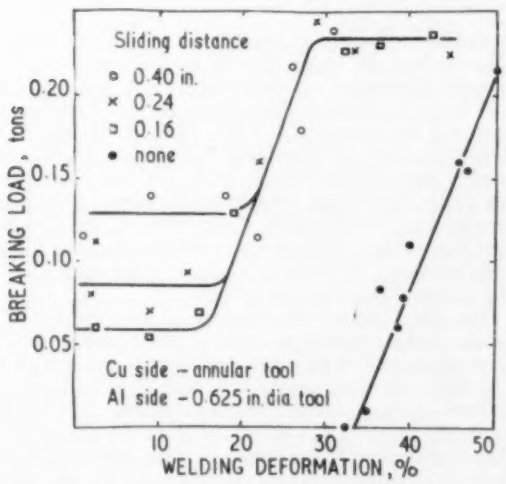
This observation is in complete accord with the suggestions previously made, that oxide on the surface of copper is the final barrier to bonding that metal to aluminium using narrow indenting tools, and that sliding between two surfaces can bring about oxide dispersal.

Lead to Copper Welds

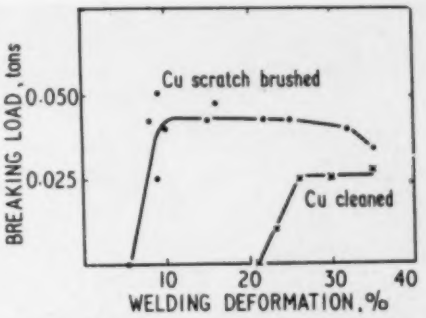
Very low deformations were sufficient to make lead adhere to copper, even when relative surface movement was not imposed. The bonds, when tested by the method previously described, were so strong that failure occurred in the lead member around the perimeter of the indentation. By contrast, the bond could easily be separated by tearing the lead away from the copper. This could be explained if the strength had been mainly derived by mechanical interlocking, particularly since the low deformation in the copper component would be unlikely to have caused oxide dispersal.

Confirmation of this was obtained by cleaning the copper surfaces with fine-grade emery paper rather than by scratch-brushing; because of the smoother surface thus produced, keying of the lead into the copper then became more difficult and greater total deformations were required to form a bond (*see* Fig. 15). During this deformation the surface of the copper became more roughened, presumably because of the different orientation of slip planes in the surface grains. This roughening probably assisted eventual bonding.

No improvement in the pressure welding characteristics of lead to copper was obtained by sliding. The operation could not produce permanent bonds at loads below those at which static loading caused adhesion, even when the sliding distance was 0·4 in., the maximum permitted by the apparatus. Penetration of lead into the cavities on the copper should have been adequate at these loads, and the results suggest that oxide on the copper had not been adequately disturbed.



14—*Effect of sliding on cold welding of copper to aluminium*



15—*Bonding of lead to copper at room temperature*

Oxide Rupture during Loading

In the foregoing assessment of the relative importance of surface films and of interfacial voids as a barrier to pressure welding, the following suggestions have been advanced about the importance of oxide dispersal:

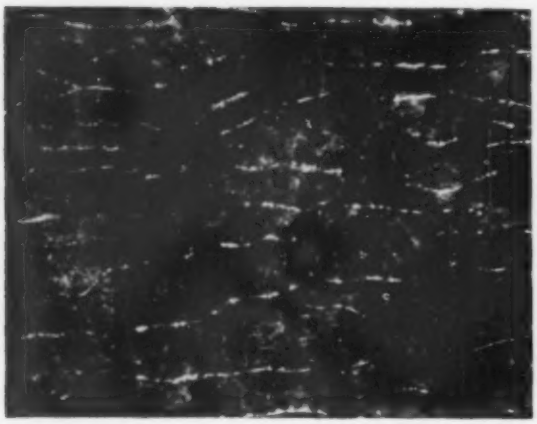
(*a*) Using annular-shaped tools for autogenous aluminium and copper welds, oxide dispersal occurs in advance of welding, interfacial voids providing the main limitation to strength

(*b*) Oxide is more difficult to disperse using 0·625 in. dia. indenters than with those of 0·2 in. dia. or of annular shape.

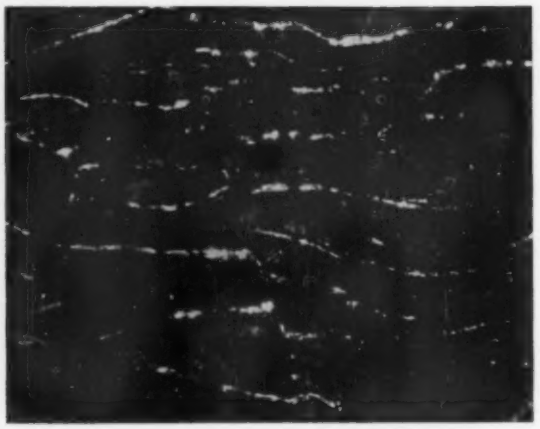
It was not possible to test these statements by optical microscopic techniques, because the films present on the strip after surface cleaning were too fine to be resolved. The method of analogy was therefore adopted, in which the fracture of anodized films at the interface of overlapped aluminium strips was studied after different amounts of indentation from each pair of pressure welding tools. The films were dyed black to provide contrast with the aluminium substrate and thus to facilitate microscopic examination. It was appreciated that the anodized layer was so different in character from the oxide film present during pressure welding as to preclude precise quantitative comparison between the two; nevertheless, it was not unreasonable to assume that the factors which were most favourable in causing rupture of the former would also most readily induce failure in the latter.

In the tests, two strips of 0·048 in. annealed and anodized aluminium were superimposed and pressed between two tools as for normal pressure welding. Predetermined amounts of deformation were imposed, and the film at the interface between the two strips was subsequently examined under the microscope.

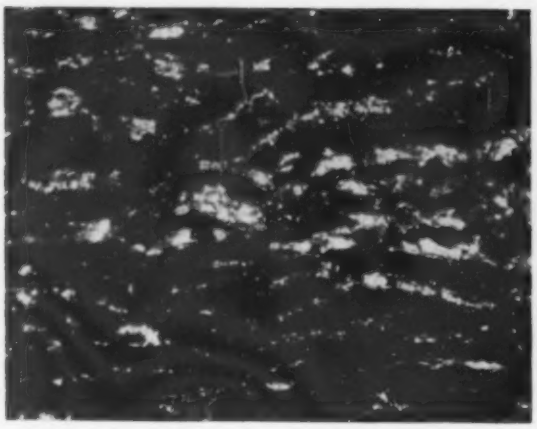
Fracture of the anodized film occurred quite readily when pressure was applied through the annular tools, being first observed after 5% deformation. The progressive increase in the extent of fracture is shown in Figs. 16 *a–c*. In marked contrast, under a load imposed by the 0·625 in. dia. tools, rupture was not obtained over most of the interfacial area after 20% deformation. Slight rupture by tearing had occurred near the periphery of the indented region (Fig. 16*d*), whilst near the centre there were isolated points at which the anodized film had been pierced. These results thus lend support to the conclusions already expressed concerning the role of oxide dispersal in pressure welding.



(*a*) Al to Al—annular tools—10% deformation



(*b*) Al to Al—annular tools—20% deformation



(*c*) Al to Al—annular tools—40% deformation

(*d*) Al to Al—0·625 in. dia. tools—20% deformation

(*e*) Al to Pb—annular tools—10% deformation

16—*Fracture of anodized films at interface of superimposed and indented strips* × 250

The observations on oxide rupture may be explained on the basis of the evidence of Nadai[10] and Bridgman,[11] that materials are made more ductile when under the influence of increased compressive forces. Thus, when the oxide film is loaded vertically, the horizontal stresses resulting from frictional restraint will increase towards the centre of the impression, and will be greatest for tools of large diameter. It would be expected, therefore, that rupture would most readily occur when narrow tools are used and that, for those of extensive area, it would begin at the periphery of the indentation. Puncturing of the film by direct piercing, on the other hand, would occur in the regions where the vertical stress was greatest, i.e. at the centre of the areas in contact.

The effect upon oxide rupture of deforming a dissimilar metal combination was studied using anodized aluminium as one member, the second being lead in one series of experiments and mild steel in another. In both cases an annular-shaped tool was used on the hard side and a 0·625 in. dia. tool on the soft side of the combination. In the presence of the softer material, the anodized film broke by extension at a slightly lower deformation than when it was in contact with a second

strip of aluminium. The amount of break-up for 10% deformation of the aluminium component is indicated in Fig. 16*e*, for comparison with the break-up shown in Fig. 16*a*. In contrast, the failure of the anodized film in the presence of a harder metal occurred by piercing rather than by extension.

Discussion

The results of the pressure welding tests described have helped to define, in a semi-quantitative manner, the relative importance of oxide dispersal and modification of surface roughness upon bond strength, particularly when sliding occurs between the members and when the frictional restraint is changed.

In autogenous welds made in aluminium or copper, using narrow annular-shaped tools, sliding between members did not assist joining by subsequent static loading even when it was known that, by double sliding action, the oxide dispersal was sufficient to produce stronger bonds than were retained after sliding. It was thus concluded that the bond strength produced in such systems by static loading was dependent upon modification of surface roughness, and that oxide dispersal was comparatively easily achieved. Support for this view was obtained by observing the extent of fracture in anodized films on the surface of aluminium strips when pressed between the same tools. In contrast, the anodized film was not readily fractured when pressed between tools of larger cross-section; further, when those tools were used for pressure welding, bonding was severely restricted.

Frictional restraint, whilst assisting the modification of surface roughness, rendered oxide dispersal more difficult. The effect of the changeover of the relative significance of the two factors was seen by welding aluminium between step-shaped tools. The strip was first indented by the smaller section of the tool to cause some break-up of oxide, but its dispersal was inhibited when the section of larger diameter made contact with the strips. The increased frictional restraint that this action simultaneously imposed assisted in the attainment of strengths approaching the maximum value when the step height was large, but was unable to do so for small step heights, since oxide dispersal occurring during indentation with the smaller part of the tool had been inadequate, and further dispersal was inhibited once the larger-diameter faces exerted their full influence.

Modification of surface asperities should be easier when joining dissimilar metals than during autogenous welding, since the lower strength of the soft component should facilitate its flow into the surface cavities of the hard. Thus oxide dispersal should be of more significance in determining bond strength, and may be the controlling factor even when welding under low restraint with narrow tools. This was deduced to be the case when welding copper to aluminium, since the degree of bonding was determined by the deformation in the harder rather than the softer component, and preliminary sliding to disperse the oxide was shown to assist subsequent welding by static loading.

Bonds made between copper and lead, although strong when tested in shear, could easily be separated by tearing the lead away from the joint. The deformation of the copper components was so small that it was unlikely that oxide dispersal had occurred. The joint strength was thus due either to bonding of lead with copper oxide or to direct mechanical interlocking. The difference in strength obtained by testing the bond in the two ways described would indicate that interlocking was the more significant factor.

The importance of these results on the development of pressure welding theory is to emphasize that the two main requirements, (*a*) oxide fracture and its subsequent dispersal, and (*b*) modification of surface roughness, are independently operative, and that their relative significance is determined both by the metals to be joined and by the design of deforming tool. Thus no theory which lays all emphasis on either factor can be expected to give a generally satisfactory indication of weldability, but those stressing oxide dispersals[4, 12] would be expected to be applicable when wide indenting tools were used, whilst for narrow tools theories stressing surface modification[6] should be more satisfactory. The manner in which increased frictional restraint facilitated the initiation of welding when using stepped tools was directly opposed to those theories[7, 8] which place emphasis on the possibility of partial or complete failure by elastic recovery for, as indicated earlier, increased restraint would involve a greater elastic recovery on release of the welding load and, in consequence, a greater degree of failure in these low-ductility bonds would have been expected.

The effect of sliding after bonding is very much dependent upon joint strength. Only welds of maximum strength made by heavy static loading were able to withstand sliding under low loads without failure.

Acknowledgments

The experiments described in this paper were undertaken in the Department of Industrial Metallurgy, Birmingham University, and thanks are due to many former colleagues in that department, particularly Mr. D. R. Milner and Dr. T. Broom, for helpful discussion during the course of the work.

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Welding
RESEARCH

B.W.R.A. REPORT

Tests on Welded Connections between I-Section Beams and Stanchions

By L. G. Johnson, M.A., A.M.I.STRUCT.E.

The general problem of the design of the welded rigid connections in multi-storey steel structures is discussed with particular reference to frames having **I***-section beams and stanchions. Descriptions are given of fifteen tests carried out on various types of joints, and their behaviour is illustrated by means of graphs showing the relationship between the applied moment and deflection at certain specified points. Conclusions are drawn from these tests and recommendations are made for use in design.*

Introduction

FOR some years there has been a growing tendency for certain architects to design multi-storey buildings in which completely uninterrupted floor space is required by the clients, who then sometimes subdivide these areas by means of very light prefabricated partitions. Such a specification precludes the use of reinforced concrete internally except, perhaps, for the floors, and this in turn means that the structural designer has to produce a frame which is rigid in itself and which does not rely on the panel walls for its stability. The design of such a frame is not usually a simple procedure, but even when the main members have been determined there remains the problem of designing the connections between these members.

The ideal connection must satisfy various theoretical and practical requirements:

Plastic theory requirements

(i) The overall stability of the structure requires that the joints shall be sensibly rigid up to the limiting moment at which a plastic hinge forms. A reasonably high degree of rigidity is also a general requirement for the application of the plastic theory. This need not mean that there shall be no rotation at all between the members joined but that any rotation should not exceed approximately 2° under the action of the full plastic moment

(ii) The joint, together with the immediately adjoining portions of the members, must be capable of plastic hinge action. This means that relative rotation between the members must be possible at an approximately constant moment of resistance. In achieving this, plastic deformation might be allowed to occur in the adjoining parts of the members, or within the joint proper. In general, however, plastic zones, developed within the joint itself, would not be sufficiently extensive to produce hinge action, hence the joint must be strong enough to withstand a plastic hinge at the end of at least one of the members joined. For a beam-to-stanchion connection, this usually means that it must be possible for a plastic hinge to develop at the end of the beam.

(iii) The joint must be capable of transmitting the necessary shear forces in the presence of the plastic hinge.

Practical considerations

(i) The connection must be cheap, simple, and so designed that it can be fabricated by normal shop practices and accommodate the usual structural tolerances

(ii) Stanchion stiffeners and welds should be kept to a minimum and should be completely fabricated in the shop

(iii) The connections should be such that, even before welding, the frame is held sufficiently rigid for lining and levelling to take place and yet not be so complex that they hamper the erection of either the main or secondary beams

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Report FE.1/55/58 of the British Welding Research Association, issued to members in July 1958.

Mr. Johnson, formerly in the Department of Engineering at Cambridge University, is General Manager of the Skeleton Steel Co. Ltd., Stratford-on-Avon.

(iv) The use of temporary fastenings or clamping devices which have to be removed after welding should be avoided

(v) Site welding must be kept to a minimum and it should be done mainly in the downhand position.

Experimental Conditions

The connections tested may be divided into two distinct types. Specimens 1 to 11 inclusive were symmetrical, having a beam attached to each flange of the stanchion, whereas specimens 12 to 15 had a beam on one flange only. The general arrangement of the two types, and the methods of loading, are shown in Figs. 16 and 17. The specimens shown in Figs. 1–11 are shown upside down as tested. In an actual structure they would of course be reversed.

Loads were applied hydraulically and were measured either directly from the machine or by means of pressure capsules. Deflections were recorded on simple dial gauges to an accuracy of 0·001 in. All joints were coated with whitewash or resin so that the formation of plastic hinges and local yielding could be observed.

Figures 18–21 show the relationship between the applied moments and the deflections of the beams, due to bending only, at the point of application of the load. The deflections due to shear have been estimated and are deducted from the observed total deflections.

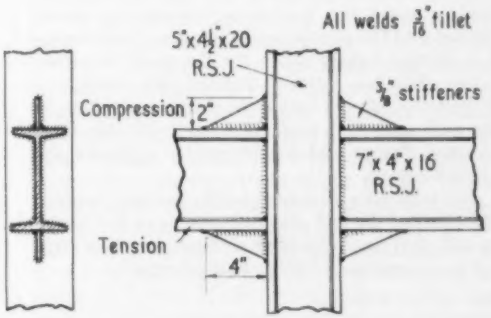
Ideally, there should be no clearance between the end of the beam and the face of the stanchion, but in practice a gap of $\frac{1}{16}$ in. or even more may be unavoidable. Some of the specimens were therefore fabricated with a specified end clearance which was maintained by means of shims during welding. For actual site conditions, however, shims would be unnecessary because both ends of the beam could be securely held before being welded to the face of the column; *e.g.*, by first welding the bottom flange of the beam to the stool cleat.

All the connections were welded up in a workshop but overhead welds were made in such a way as to simulate as far as possible actual site conditions. The types of electrode used were to BS.1719 classifications E.319 and E.217. All the welding was carried out by an experienced welder under close supervision. Each specimen was carefully examined after structural testing and, where necessary, the joint was cut open so that the fracture surfaces of the weld could be inspected. No serious defects were found in the weld structure of any of the specimens described in this report.

Results of Tests

SPECIMEN 1

As the load was increased there was a steady increase in deflection, but the stanchion showed no sign of local deformation or yielding even at the failure load. At a moment of about 135 tons in. the weld at the extreme tip of one of the gussets on the tension side failed and the crack spread quickly upwards as far as the middle of the web of the 7×4 in. beam. This moment corresponded to a fibre stress of about 12 tons/sq.in. in the flange of the joist.



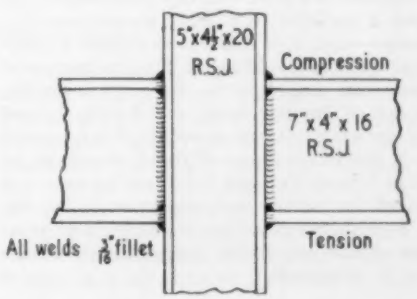
1—*Specimen 1*

SPECIMEN 2

This was an exact reproduction of specimen 1 except that the triangular gussets were omitted. The joint also failed when a crack formed in one of the tension flange welds and spread immediately across the whole of the flange and about $2\frac{1}{2}$ in. up the web. Unfortunately it was not possible to observe the exact position of the initial weld fracture.

Failure occurred at a moment of about 155 tons in., equivalent to a stress of 13·5 tons/sq.in. in the flange of the 7×4 in. joist. Although this ultimate moment was greater than that attained by specimen 1, the moment/deflection curves show that the connection was slightly less rigid than the first specimen. But neither of the connections were capable of transmitting the full plastic moment of the beam. Local deformation was not observed at any point in the beams or stanchion and there was no evidence of any yielding.

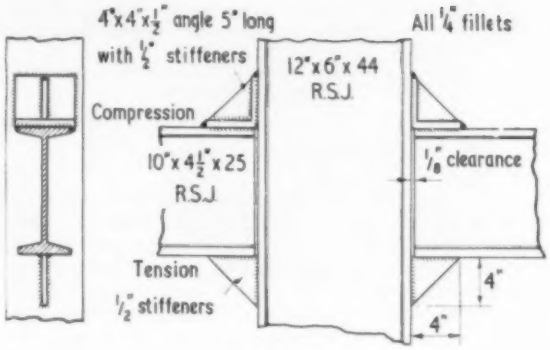
2—*Specimen 2*



SPECIMEN 3

This was an attempt to investigate the behaviour of a connection with a triangular gusset plate connecting the tension flange of a beam to the face of a stanchion. The compression flange rested on a stiffened angle cleat.

As anticipated, the joint did not transmit a very large moment, and a weld fractured in tension at a moment corresponding to a flange bending stress of approx. 6·5 tons/sq.in. Before failure, there were signs of yield in the tension side gusset plates but there was no deformation or yield at any other part of the joint. The weld fracture itself commenced adjacent to the right-angled corner and spread outwards along the stanchion flange, unlike that in specimen 1.



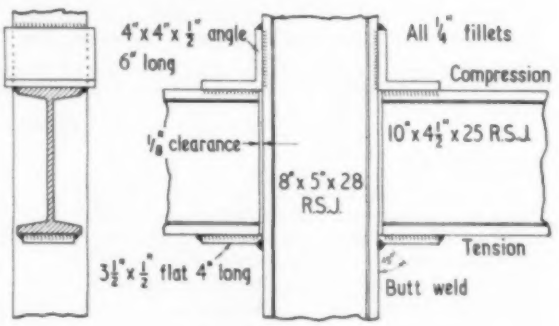
3—*Specimen 3*

SPECIMEN 4

An attempt was made in this specimen to produce a site joint that could be completely welded in the downhand position. This involved the use of a seating cleat projecting beyond the flanges of the beam and, on the tension side, a ½-in. plate which was prepared along one edge for a 45° single **V** butt weld, the other three sides being fillet welded to the flange of the beam. The bevelled plate was stopped back $\frac{3}{16}$ in. from the stanchion face.

At a moment of about 350 tons in. the fillet welds joining the beams to the seating cleats yielded and the compression flanges of the beams then butted tightly up to the flange of the stanchion. Further loading caused the stanchion flanges to deform locally leading to yielding in the web near the root fillet opposite the compression flange and in the centre opposite the tension flange.

The load was increased until it almost reached the value of the full plastic moment of the beam, by which time deflections had grown very large but no actual weld failure had occurred.

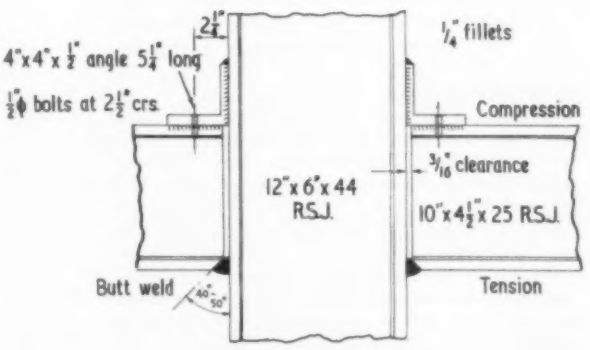


4—*Specimen 4*

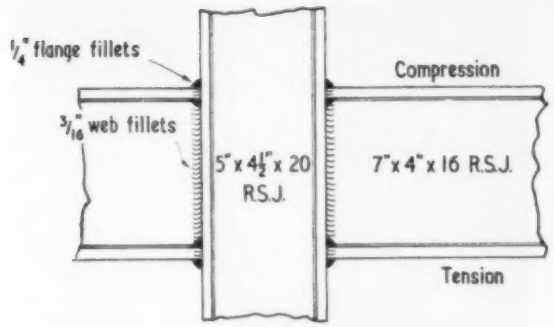
SPECIMEN 5

The 10 × 4½ in. beams were first bolted to the stool cleats and were then downhand fillet welded along the toes of the flanges. Then single **V** butt welds were made between the tension flanges of the beams and the face of the stanchion, the clearance of $\frac{3}{16}$ in. being allowed to facilitate welding. This type of weld preparation when applied to a joist with tapered flanges does not give a uniform root face—an obvious disadvantage—and it is difficult to obtain a satisfactory first run of weld metal. For this particular specimen, no sealing runs were made to the under side of the butt welds, and during the test one of the welds cracked suddenly at the bottom of the **V** at a flange stress of about 11 tons/sq.in.

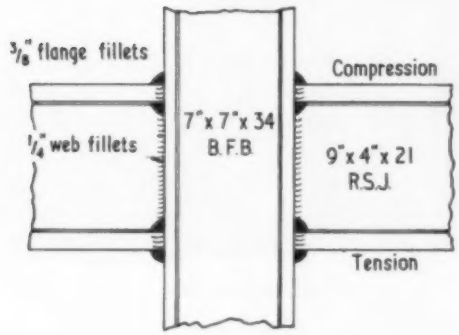
Before failure, the joint behaved in a way that compared favourably with specimen 4, but the quite unpredicted cracking of the weld allowed no real indication of the true strength of the joint to be obtained.



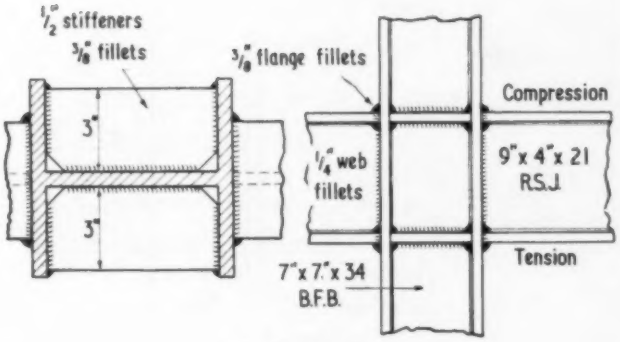
5—*Specimen 5*



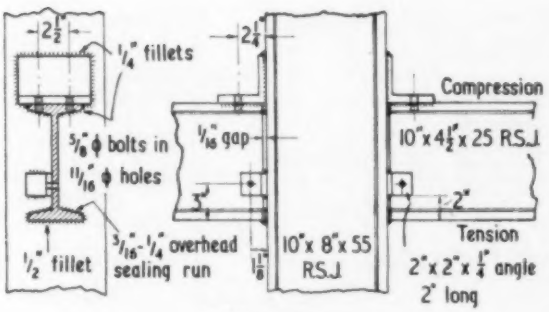
6—*Specimen 6*



7—*Specimen 7*



8—*Specimen 8*



9—*Specimen 9*

SPECIMEN 6

This was the same as specimen 2 except for the increase in size of the flange fillet welds from $\frac{3}{16}$ in. to $\frac{1}{4}$ in. The two main effects of this increase in weld size were to produce a more rigid moment/deflection characteristic and to enable the joint to transmit the theoretical full plastic moment of the beam; this was accompanied by appreciable deflection in the later stages.

Local deformation in the flanges of the stanchion took place, and there was also evidence of both yielding and buckling in the web opposite the compression flanges of the beams. At a moment slightly greater than the theoretical full plastic value one of the tension flange welds failed in exactly the same way as specimen 2.

SPECIMENS 7 and 8

These two connections were identical except for the web reinforcement of specimen 8. The throat areas of the flange welds were approximately equal to the corresponding areas of the adjacent flanges and webs.

Specimen 8 exhibited moment/deflection characteristics far superior to those obtained from specimen 7, especially at the higher moments. The stanchion showed no visible signs of distress at any stage during the test and there was no weld failure at any part of the joint. Plastic hinges developed in each beam adjacent to the stanchion flange and these gave rise to large deflections at a more or less constant moment. Specimen 7, on the other hand, did not sustain a sufficiently high moment to develop plastic hinges in the beams, although the ultimate moment almost reached the theoretical full plastic value. Yield in the web of the stanchion, in an area between the tension flanges of the beams, commenced when the stress in the flanges reached about 9 tons/sq.in. From that point, local flange buckling of the stanchion developed until a tension flange weld failed at a moment of about 315 tons in. It was significant that this weld fracture commenced in the inner tension flange fillet weld adjacent to the root fillet, the crack spreading outwards to the toes of the flanges and then very quickly across the outer fillet weld. This particular form of weld failure was observed in a number of subsequent tests, and usually occurred when the stanchion was not stiffened or when the weld was stopped at the root fillet instead of being continued down the web of the beam.

SPECIMEN 9

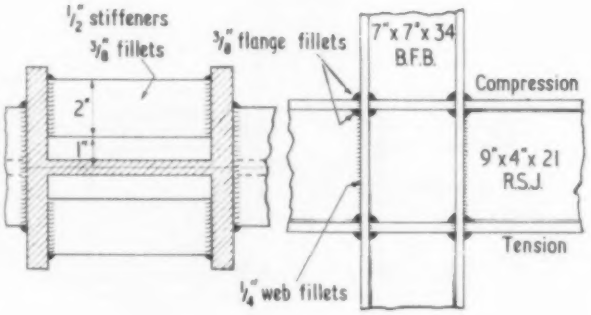
A more practical type of connection was produced in this specimen. The beams were located on the seating cleats with black bolts in clearance holes, and small web cleats were added to facilitate erection. There was no welding down the webs of the beams and stiffeners were not provided to the stanchion.

On applying the load, yield was noted in the web of the stanchion, firstly between the tension flanges at a moment of 210 tons in. and then

between the compression flanges at a moment of 300 tons in. Further loading produced little deformation in the joint, but at a moment of 460 tons in. one pair of inner tension flange welds fractured near the root fillet and the cracks spread immediately to the toes of the beam. These cracks, however, did not spread to the outer $\frac{1}{4}$ in. fillet weld until the moment was increased to 500 tons in. This moment is greater than the theoretical full plastic value for a $10 \times 4\frac{1}{2}$ in. joist but it was not reached until appreciable deformation had taken place (Fig. 20).

SPECIMEN 10

This was a simple modification of specimen 8, the stiffeners being reduced in width to 2 in. and they were not welded to the web of the stanchion. Again, a good moment/deflection relationship was obtained, the theoretical full plastic moment being easily exceeded, with all welds remaining intact throughout the test. In the working range, however, specimen 8 appeared to be the more rigid of the two connections although the actual difference was very slight. It must be remembered, of course, that stiffeners not connected to the stanchion web are unsuitable for beams with unequal end moments because they cannot transfer the out-of-balance forces from the beams to the stanchion.

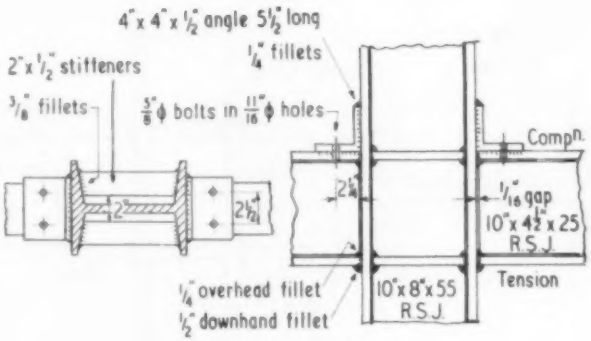


10—*Specimen 10*

SPECIMEN 11

This also was a practical type of joint, basically similar to specimen 9 but with the addition of stanchion flange stiffeners clear of the web, as in specimen 10.

These modifications resulted in a considerable increase in the rigidity of the joint (Fig. 20). In the working range, the connection behaved almost ideally, the full plastic moment being reached with a deflection of only 0·4 in. As the load was increased still further, there were signs that plastic hinges were forming, and the deflections increased more rapidly until a moment of 510 tons in. was reached, when the inner tension flange welds again failed adjacent to the root fillets. Unlike specimen 9, however, the cracks quickly spread to the $\frac{1}{4}$ in. downhand fillet weld without any further increase in the applied load.

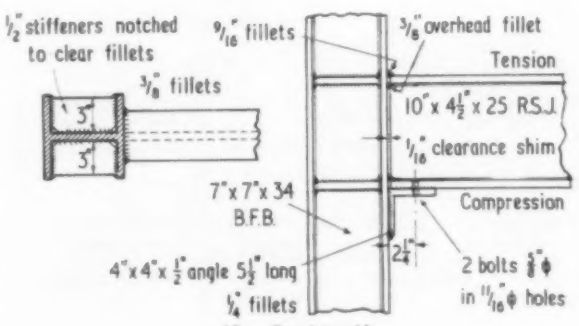


11—*Specimen 11*

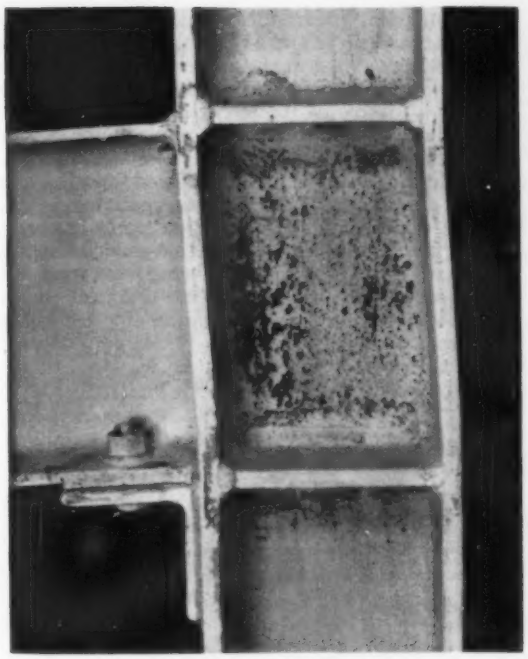
SPECIMEN 12

The stanchion web of this one-sided connection was stiffened like that of specimen 8. The stool cleat was drilled to suit site erection conditions and the joint was made by means of fillet welds to both flanges. The end clearance was maintained at $\frac{1}{16}$ in. and the web of the beam was not welded to the stanchion, it being assumed that the shear force was adequately taken by the stool cleat.

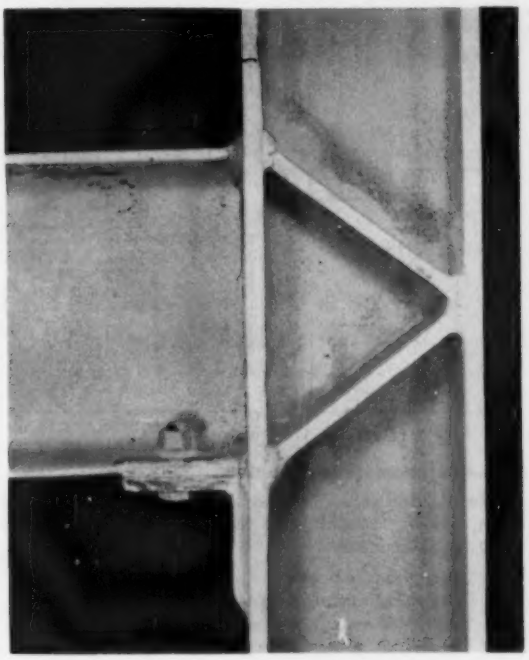
At a moment of 280 tons in., the stanchion web between the stiffeners commenced to yield, and by the time 340 tons in. had been reached, the whole of this area showed evidence of yield.



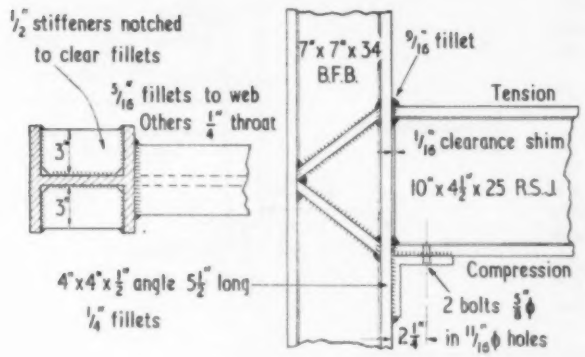
12a—*Specimen 12*



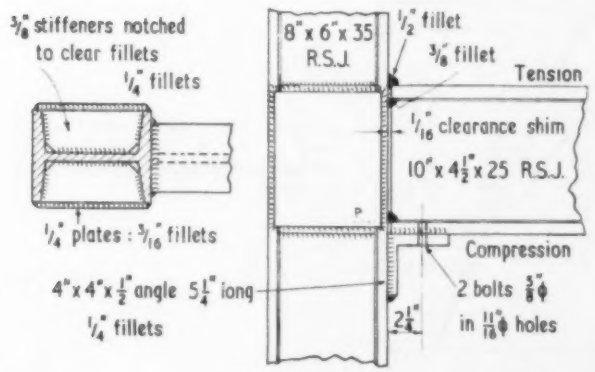
12b—*Specimen 12 after testing*



13b—*Specimen 13 after testing*



13a—*Specimen 13*



14—*Specimen 14*

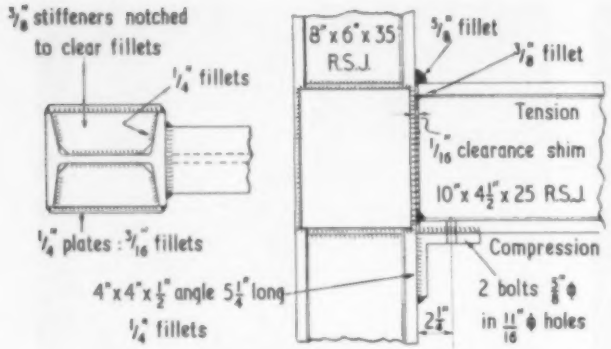
Further increase in load resulted in considerable deformation in that part of the stanchion contained by the stiffeners (Fig. 12*b*). Elsewhere there was no evidence of yield, local deformation or weld failure even when the moment was increased to 490 tons in.

SPECIMEN 13

Because of the very unsatisfactory behaviour of specimen 12, the stiffeners were modified as shown in Figs. 13*a* and 13*b*, the actual beam-to-stanchion connection remaining unaltered. A very considerable increase in stiffness resulted from this change and there was no sign of yield at any point in the stanchion during the test. The moment/deflection relationship remained almost linear until the full plastic moment was reached, whereupon a hinge developed in the beam and deflections increased more rapidly. At a moment of about 530 tons in. the test had to be discontinued because of these very large deflections, but all the welds remained intact.

SPECIMENS 14 and 15

One disadvantage of stiffeners is that they tend to complicate the erection of any secondary beams that frame into the web of the stanchion. Specimens 14 and 15 were attempts to overcome this difficulty by covering the stiffeners with ¼ in. plates welded to the toes of the flanges of the stanchion and also to the edges of the stiffeners. The arrangement of the stiffeners was identical with that for specimen 12 but the thickness and weld sizes were reduced. Specimen 14 had the



15—*Specimen 15*

Conclusions

Beam-to-stanchion flange connections

This limited series of tests seems to indicate that the detail used for specimen 15 would make a satisfactory connection because:

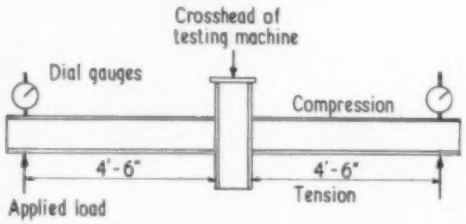
(*a*) It is simple to fabricate
(*b*) Erection is straightforward
(*c*) Most of the welding is either downhand or vertical
(*d*) The design uses normal structural tolerances
(*e*) The joint will transmit a moment appreciably greater than the theoretical full plastic value of the beam.

Since the end shear force is taken by the web welds the connection could in fact be improved by reducing the size of the stool cleat and thus decreasing the amount of shop welding.

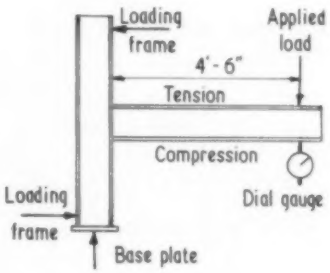
Stanchion flanges without stiffeners

The tests show that it is most unwise to use an unstiffened stanchion, because the flexibility of the flanges results in stress concentrations in the beam-to-stanchion flange connection. This fact has been widely known for some time but it is perhaps not always realized that the weld failure itself usually starts in the corner near the root fillet of the tension flange of the beam. Even with stiffeners, this tendency still exists but same type of beam-to-stanchion face connection as specimens 12 and 13, but specimen 15 had, in addition, a fillet weld down each side of the web of the beam. This was introduced primarily to try to overcome the tendency for tension weld failures to commence at a point in the corner near the root fillet of the beam.

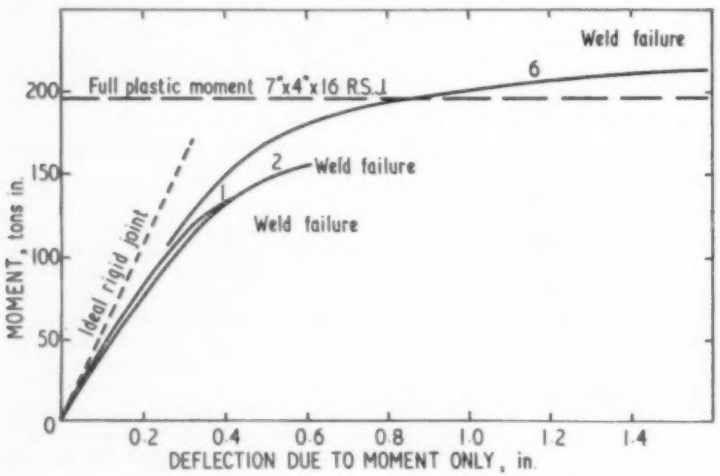
In the tests specimen 14 suffered weld fracture in exactly this way, whereas specimen 15 remained intact throughout. Both joints, however, exhibited very satisfactory moment deflection characteristics and proved themselves capable of transmitting the full plastic moment of a $10 \times 4\frac{1}{2}$ in. joist without causing any distress to the stanchion.



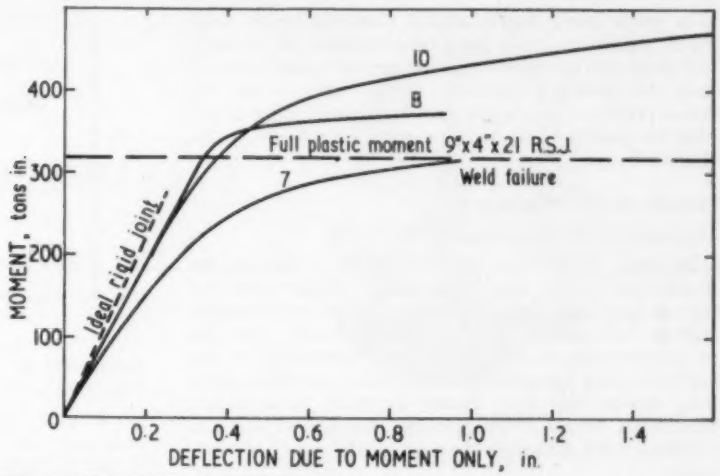
16—*Method of loading specimens 1–11*



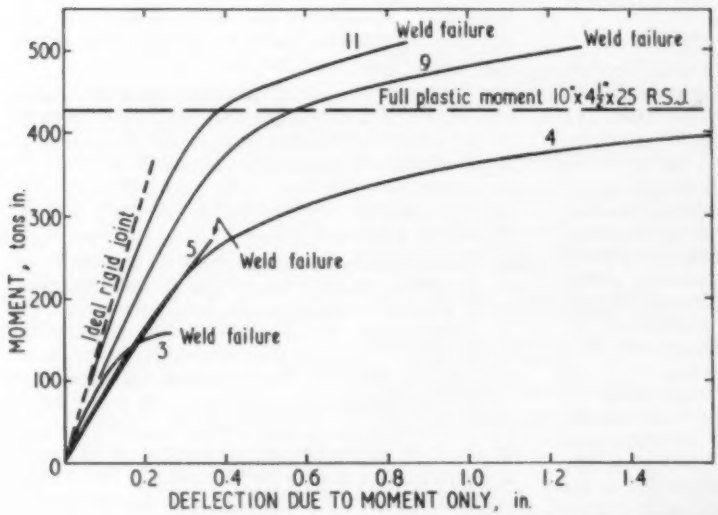
17—*Method of loading specimens 12–15*



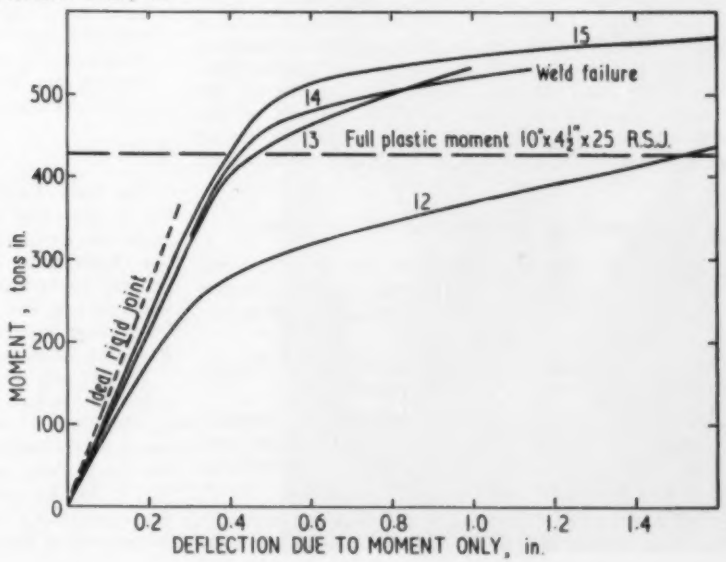
18—*Moment/deflection curves for specimens 1, 2 and 6*



19—
Moment/deflection curves for specimens 7, 8 and 10



20—
Moment/deflection curves for specimens 3, 4, 5, 9 and 11



21—
Moment/deflection curves for specimens 12, 13, 14, and 15

to a much lesser degree and it does not occur until much higher moments have been reached. It is therefore desirable to obviate this danger, to some extent at least, by having a continuous fillet weld round the entire profile of the beam, particular care being taken with the quality of the weld near the root fillets of the tension flange.

Stanchion flanges with stiffeners

One-sided connections (specimens 12–15)

In these connections large shear forces have to be transmitted to the stanchion, and it is clear from the test on specimen 12 that the normal type of horizontal stiffener will seldom give satisfactory results. It leads to overstressing in the area of the web between the stiffeners, and appreciable deformation can take place long before the full plastic moment is attained. Specimens 13 and 15 are suitable alternatives, and are recommended although they are more costly to produce.

Double-sided connections (specimens 1–11)

The requirements of these types of connection are somewhat simpler, because only the out-of-balance moment has to be transmitted to the stanchion. The horizontal stiffener is therefore generally adequate; for nearly equal loads the stiffeners need not even be welded to the web of the stanchion. There remains, of course, the very real problem of accommodating secondary beams framing into the web of the stanchion, and it is quite likely that side plates, as used in specimens 14 and 15, will have to be used for purely practical considerations in addition to the normal type of stiffener. Unfortunately, sufficient evidence is not yet available to enable minimum stiffener and weld sizes to be specified, but further work is being done on this problem. At present it can be stated that the stiffeners should not be larger than the beam flanges and that the welds to the compression stiffeners need not be as big as those for the tension stiffeners. The stiffeners themselves must be accurately shaped to the correct profile of the stanchion but they do not need to be a driving fit because the contraction due to welding is usually sufficient to ensure tightness. Pre-stressing of the stanchion web and stiffeners is undoubtedly produced by this welding, but the magnitude of the stresses must be very variable, for it depends on the relative size of the various components, the initial degree of fit of the stiffeners, and the sizes of the welds.

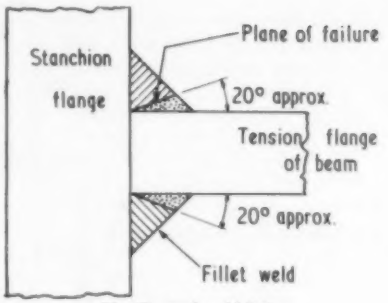
Summary and Recommendations for Design

These tests were of a somewhat random nature but they have given results which lead to the following recommendations for the design of fully rigid beam-to-stanchion connections:

(1) It is essential to provide some form of stiffening between the flanges of the stanchions.

(2) If the beams on both flanges of a connection are equal in size, and have invariable identical end moments, it is unnecessary to weld the horizontal type of stiffener to the web of the stanchion.

(3) For a joint with a beam on one flange only, the use of horizontal stiffeners opposite the flanges of the beam will be unsatisfactory unless the stanchion web is capable of sustaining very high shear forces.



22—*Typical weld failure*

(4) In every specimen with stiffeners, all the welds fastening the stiffeners to the stanchions remained intact throughout the tests. It seems, therefore, that smaller welds would be just as satisfactory, especially for compression stiffeners where some of the load can be taken in direct bearing.

(5) The beam-to-stanchion flange connection should be capable of transmitting the full plastic moment of the beam if the throat area of the weld is made equal to the corresponding cross-sectional area of the beam, due allowance being made, of course, for any clearance between the end of the beam and the face of the stanchion.

(6) Every weld failure began near the tension flange of the beam, and it was significant that the initial crack almost invariably started near the root fillet. It is important, therefore, to design the tension flange welds to develop the full strength of the flange and also to continue these welds down the web to avoid any discontinuity adjacent to the root fillet.

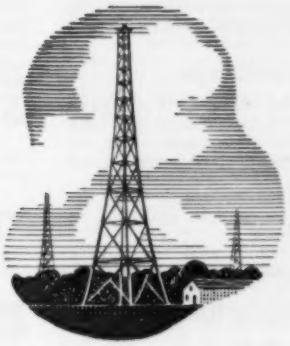
(7) Every weld failure occurred in a plane inclined at about 20° to the direction of the principal forces, compared with the 45° which is normally assumed in practice (Fig. 22). It is thought that this factor may have some significance, especially when dealing with the larger weld sizes where it would perhaps be advantageous to use fillet welds having unequal leg lengths. But further work will have to be undertaken before definite recommendations can be made.

Acknowledgments

The work described in this report was carried out at the Engineering Laboratory, Cambridge University, under the direction of Professor J. F. Baker, Head of the Department of Engineering. It forms part of a general investigation into the behaviour of steel structures in the plastic range, being carried out at Cambridge with the support of the British Welding Research Association.

Thanks are due to Mr. R. H. C. Wilkes, a post-graduate student attending the course on Structures and Strength of Materials at the University, who made many useful suggestions and also helped to carry out the tests. Acknowledgment must also be made to Mr. J. M. Stevenson of Messrs. Harland and Wolff who very kindly supplied much of the steel used in the fabrication of the specimens.

NEWS
and Announcements



News of the Institute and Branches
B.W.R.A. · Other Societies · and Industry

INSTITUTE ACTIVITIES

MEETINGS

Meeting on 'Hydrogen in Weld Metal'

The Joint Meeting with the Iron and Steel Institute was held at the offices of the Institution of Naval Architects on Wednesday, 10th December.

Mr. William Barr presided, and there was an attendance of over 70 to discuss six papers, four presented by Mr. P. D. Blake, and two by Dr. Christensen.

The discussion was opened by Dr. Hoar of the University of Cambridge, and it was extremely well maintained at a high level for over three hours.

Spring Meeting, 1959

For the first time, the Spring Meeting of the Institute will be held in London, and will coincide with the Engineering, Marine, Welding, and Nuclear Energy Exhibition at Olympia.

The meeting will open with a reception at the Institute on the evening of Monday, 20th April. There will be a choice of Works Visits on Tuesday, 21st and Thursday, 23rd April. All but one of these visits will occupy the morning only, so as to allow members to go to the Exhibition in the afternoon and evening if they wish to do so.

On the mornings of Wednesday and Friday, 22nd and 24th April, there will be discussion meetings at the Institute, when the four papers on the Low-Temperature Properties of Aluminium Alloys (published in the November 1958 issue of the *Journal*) will be presented and discussed, as well as a group of five papers bearing on the general theme of the Economics of Welding, especially in the structural field.

On the Wednesday evening, members attending the Spring Meeting will be able to go to the London Branches Joint Dinner at the Connaught Rooms.

The following firms have already agreed to receive works visits. Parties will travel by coach from the Institute:

A.P.V. Company Ltd.
British Oxygen Gases Ltd.
Dawnays Ltd.
Ford Motor Co. Ltd.
G. A. Harvey & Co. (London) Ltd.
Geo. W. King Ltd.
Vickers-Armstrongs Ltd.
British Oxygen Research & Development Ltd.

School of Welding Technology

The following are the courses which have been arranged for the first part of 1959. There are still some vacancies, but places are now being rapidly filled, and immediate application is advised.

12th–16th Jan.	Training, Testing, and Approval of Welders
9th–13th Feb.	Brazing Technology and Design
23rd–25th Feb.	Welded Storage Tanks
2nd–4th March	Metal Spraying
16th–20th March	Welding Design and Construction in Corrosion- and Heat-Resisting Materials

Gift of Projection Screen

The South London Branch has given the Institute for its Lecture Hall a projection screen for use at lectures and courses in the School of Welding Technology. The Council has recorded its gratitude for this gift.

Sir Charles Lillicrap

The Council of the Institute has conferred a Fellowship upon Sir Charles Lillicrap, K.C.B., M.B.E., D.Sc., in recognition of his distinguished services to welding and the

At the Annual Dinner

The President, Mr. John Strong (right), talks with the Parliamentary Secretary to the Ministry of Supply, Mr. W. J. Taylor (left), and Mr. T. Potts.

Institute. Sir Charles, formerly Director of Naval Construction, has for some years been President of both the Institute and the British Welding Research Association.

Appointments

With the revised make-up of the News Section into three columns it has been decided to revise the charges made for advertisements relating to situations vacant and required.

The new arrangements are shown at the end of the News Section, and will be repeated each month.

PUBLICATIONS

Index

The combined subject and name index, and preliminary matter, for volume 5 of the *British Welding Journal*, covering the twelve issues from January to December 1958, is distributed with this issue. Additional copies, if needed, may be had on application to the Secretary, Institute of Welding, 54 Princes Gate, London S.W.7.

Binding of Journal

Many members probably make their own arrangements for binding copies of the Journal, and the Institute has yet made no provision for binding volumes in bulk. If there is sufficient demand, however, the Institute would provide a service whereby numbers of sets of copies could be bound at one time at an economic price (probably between 10s. and 20s. including postage).

Requests for this service should be addressed to the Secretary, but *no Journals* should be sent. When sufficient enquiries have been received there will be a notification of when and to where the copies are to be sent. This will ensure the minimum period during which the copies are not available for reference.

NEWS OF MEMBERS

Mr. William Barr, O.B.E., has been nominated by the Council of the Iron and Steel Institute for election as President of that Society for the 1959–60 session. He will take office at the Annual General Meeting of the Institute on 6th May 1959.

Mr. Barr, who has been Honorary Treasurer of the Iron and Steel Institute since 1953, has been a member of the Research Board of the British Welding Research Association for a number of years. He has also served on many welding committees and on Commissions of the International Institute of Welding.

L. Redshaw, a Director and Shipbuilding General Manager of Vickers-Armstrongs (Shipbuilding) Ltd., has been elected Chairman of the Conference and Works Board of the Shipbuilding Employers' Federation.

The Council regret to record the death of **Mr. Gordon G. Musted,** one of the best known figures among the British pioneers of welding, who was killed in a motor car accident on 1st December.

Mr. Musted joined the Institute in 1931, when he was in charge of the Engineering and Welding Section of the Government Training Centre in Garrison Lane, Birmingham; but his welding experience went back long before then, on the Mersey Shipyards. For many years he was employed by Quasi-Arc Ltd. as an instructor, and when he retired about five years ago he set up as a private consultant.

He had a natural gift for putting his wide and varied knowledge of practical welding problems into simple and effective form to students, and his attractive personality made him one of the best-loved lecturers all over the country. He was the author of several prize-winning papers in the competitions sponsored by the James F. Lincoln Welding Foundation, and only in November last he completed a paper for the International Institute of Welding Assembly in Yugoslavia.

Mr. Musted was married, and his son, Mr. George Musted, joined the Institute in 1944.

BRANCH NEWS—Reports of Meetings

East Midlands

Welded pipework

At the meeting held on 15th October at the Welbeck Hotel, the retiring President, Wing Commander J. M. Aiton, presented the Presidential Insignia to his successor, Mr. H. L. Palmer.

The lecturer for the evening, Mr. W. L. Roe, is a Branch member, who has served on the Committee for several years and is also a past Chairman. His subject was *Welding of High-Temperature and High-Pressure Pipework*.

Mr. Roe gave details of the types of steel normally used for these applications, together with recommendations for the limits of service temperatures. Numerous slides were shown of weld preparations for butt, branch, and flange connections, and particular emphasis was given to the importance of correct preparation and set-up. Mr. Roe stressed the vital importance of adhering to the specified dimensions for root faces and root gaps if the first runs were to be of high quality. He recommended that neck flanges should be used for all alloy steel piping because of the unsatisfactory experience in service with welded-on slab-type flanges.

It was stated that alloy steels should be welded by the metal-arc process, for this provided a greater degree of consistency in the weld metal properties than other processes. Where the fluid to be carried was likely to cause stress corrosion it was important that both alloy steel and mild steel welds should be suitably heat-treated.

The lecturer introduced a useful service to those attending by the distribution of sheets giving references and comprehensive details of pre- and post-welding heat-treatments. K.H.E.

Liverpool

Arc welding processes

Members had taken to heart the attendance appeal of the Chairman, and turned up in force to hear Mr. E. Flintham, who opened the first meeting of the 1958/59 session with an outstanding practical paper on *The Selection and Use of Arc Welding Processes*.

Mr. Flintham referred to several significant developments in the production of manual electrodes, and gave some valuable comparisons between the low-hydrogen and iron powder electrodes and the more conventional types. It seemed evident that these highly economic electrodes were not being applied in industry as rapidly as they should be.

The lecturer gave concise descriptions of the two major automatic welding processes —open-arc and submerged-arc—and described many of the special applications that have been evolved from them. He referred in particular to the increasing need in the shipyards for the rapid deposition of double fillet welds for attaching stiffeners to hull assemblies. This had led to the development of large gantry-type travelling machines carrying automatic welding heads.

Mr. Flintham drew attention to developments in the inert-gas shielded-arc processes and described some examples of their use in the welding of aluminium alloys. He also referred to welding processes for joining stainless steels and for reclaiming eroded bronze propellers, and outlined the probable advantages of the newer CO_2 shielded process for welding structural work.

During the lively discussion Mr. Flintham replied to many interesting questions, particularly in relation to iron powder electrodes, and the relative amount of automatic welding being used in Britain. H.R.C.

Sheffield

Repairs to castings

A meeting was held on Monday 10th November, when an interesting lecture, followed by a lengthy discussion, was given on the *Gussolite Process of Repairs to Iron Castings*, by Mr. D. H. Jones. There were approximately 40 people in attendance. J.S.W.

South London

Brittle fracture

A meeting was held at Headquarters on 13th November when 46 members and visitors attended to hear Dr. W. D. Biggs lecture on *Welding and Brittle Fracture*. After examining the historical evidence the author indicated that brittle fracture always occurs at high velocity with low ductility, usually at low temperatures and often outside the welds. The fractures frequently do not follow the welds, but run through the parent metal instead. It has been found that killed steels are superior to semi-killed or rimming steels because they are less fracture sensitive. He considered that residual welding stresses were unimportant unless they were associated with defects on the surface of the plate or within the welds or resulted from design faults.

He pointed out that, theoretically, if the yield stress is greater than the fracture stress there could only be elastic deformation up to failure, but that when the fracture stress was greater than the yield stress there would be plastic deformation; either of these conditions could inhibit brittle fracture. It had been found that the energy absorbed in impact tests was proportional to the radius at the root of the notch. It had also been noted that the yield stress of mild steel increases with falling temperature, and as the strain rate increased so the yield stress and fracture stress increased. He commented upon the criterion of the impact transition curve, suggesting that 15 ft.lb Charpy **V**-notch value and the percentage area of the fracture that was brittle could be misleading, because both were arbitrary values which, although based on experience, did not stand up to critical examination. There were some tests that were useful for design purposes but in general they were too large to be carried out in any quantity. In his opinion the impact tests should be used as an exclusive test rather than an acceptance one.

Dr. Biggs discussed the importance of the chemical composition of parent plate, and pointed out the value and limitations of the Mn–C ratio. He also referred to the influence of carbon, phosphorus, and silicon in increasing the tendency to brittle failure, and of manganese and nickel in decreasing it. After discussing the influence of metallurgical structure, with respect to the direction of rolling and its influence in multipass welds, which should not be rated at impact transition values greater than the plate unless a large number of tests were carried out, he concluded with the opinion that the best designs today coupled with high-grade fabricating techniques should overcome most of the difficulties. During a lengthy discussion many aspects were raised, including that of stress-relieving, which Dr. Biggs considered to be beneficial provided that the weld metal had no tendencies to secondary hardening. E.B.G.T.

Medway Section—Testing

The first meeting of the season of the Medway Section was held on 22nd October, at Messrs. Fredk. Braby & Co. Ltd., Crayford, before an appreciative audience of 54, when an illustrated lecture on *Weld Inspection by Non-Destructive Methods*, was given by Mr. D. T. Carter. He discussed the various forms of defects which can lead to potential failure and gave a detailed explanation of the methods of detection, from the time-honoured chalk and paraffin to crack detection, dye-penetrant, fluorescent penetrant with ultra-violet light, magnetic flux detection, ultra-sonic testing and radiographic examination.

During the ensuing discussion the relative values and limitations of X-ray and gamma rays were enlarged upon. F.W.M.

South Wales

Heavy plant repairs

At Swansea and at Cardiff on 3rd and 4th November respectively, Mr. G. Gordon Musted, A.C.T. (Birmingham) read a paper entitled *Reclamation of Heavy Plant and Machinery by Practical Welding Application*. The author presented some typical examples of maintenance and reclamation problems, and explained how to do this class of repair work, especially for heavy sections. He showed how these are made good and safe for further service, thus preventing bottle-necks in production, and thereby increasing productivity at lower cost by the use of practical welding applications such as oxy-acetylene welding and cutting, metal-arc welding, and the carbon-arc process. L.M.

South Western

Tubular structures

A lecture on *Welding of Tubular Structures* was given by Mr. G. B. Godfrey at the meeting held at Radiant House, Bristol, on 4th November.

Mr. Godfrey illustrated his remarks with some excellent slides showing recent structures, both in this country and abroad, and commented on the great advances made on the Continent in the field of tubular construction. This meeting attracted a high proportion of visitors, especially from the constructional engineering industry.

Resistance welding

A second meeting in November, on 19th, was also held at Radiant House, when Mr. McDowell and Mr. Weeks, both members of the Branch, jointly presented a paper on *Practical Aspects of Resistance Welding*. They dealt most thoroughly with their subject, and it was interesting to note that the metallurgical side of the materials considered was a most important factor in using the process. This was particularly evident in the aircraft industry, which is well represented in the Bristol area. A vote of thanks to the authors for an extremely interesting paper was given by Dr. Cottrell of the Bristol Aircraft Co. G.R.T.

Wolverhampton

Reactor vessel supports

At the meeting on 12th November, Mr. J. A. Forrest presented a most interesting paper on *Welding and Testing of Skirt Supports for Spherical Pressure Vessels*. He opened his paper by outlining the functional differences between the skirt support for the Dounreay sphere and that for the reactor pressure vessel at present under construction at Hunterston. At Dounreay the plate thickness of the 135 ft dia. vessel varied between 1 and 1$\frac{1}{8}$ in., the total weight transmitted to the skirt support being 8000 tons. The Hunterston vessel is 70 ft dia., the plate thickness 2$\frac{1}{4}$ in., and the overall weight 5500 tons. Windloads were an important consideration at Dounreay, but at Hunterston stresses from differential thermal expansion were more important.

The advantages claimed for a skirt support system are continuity, flexibility, and stability, but Mr. Forrest mentioned that alternatives had been considered, such as suspending the entire vessel from above. To check the practicability of fabricating the skirt-to-vessel connection, two full-size mock-ups were constructed in the works to represent a 5-ft length of this joint. A forged connection had been considered, but was ruled out on the grounds that this type of forging would be difficult to make and its quality could not be guaranteed. All the root runs of the welds were made with 6 and 4 s.w.g. electrodes, and 10 and 8 s.w.g. sizes were used solely for producing the correct profile to the finished welds. Overhead welding was avoided by turning over the entire fabrication after the completion of the outer skirt weld. One of the subsidiary objectives on the first mock-up was to compare the effectiveness of various systems of non-destructive testing, and the following methods were used:

1. Radiographic examination, using 400 kV X-ray, and 320 and 1000 curie cobalt–60 gamma-ray sources.
2. Magnetic crack detection.
3. Ultrasonic examination.

A sensitivity of 1$\frac{1}{2}$% was required; *i.e.*, a defect of 0·045 in. should be discernible. The best radiographic results were obtained with a triple-film lead screen technique, with an exposure time of 55 min. at 390 kV. In some places the combined metal thickness amounted to 5$\frac{3}{4}$ in. The ultrasonic method involved the solution of a number of problems, among them the provision of a permanent record showing the exact position and size of the faults. The lecturer described an interesting mechanical/photographic method adopted for this purpose.

Mr. Forrest concluded his paper with a short description of the second mock-up, in which special arrangements were made to control the distortion and alignment of the inner and outer skirts. Direct current welding rectifiers were used in making this mock-up in preference to a.c.

An interesting discussion was opened by Mr. S. H. Griffiths, and the author replied to the various questions as follows: Radiation monitoring had shown that effective protection to personnel 5 ft away was given by lead cones and lead-backed cassettes. Direct welding current was preferred for site work, owing to the reduction in start-of-weld porosity, and no difficulties had been encountered with arc blow. Stress relief of the joint between the skirt and the vessel was to be done electrically using Nimonic tape absorbing 560 kW. No residual stresses were expected to remain after stress relieving the vessel, but small stresses might still remain after heat-treatment of the diagrid frame.

Before the meeting closed, Mr. Jukes proposed a vote of thanks to Mr. Forrest for dealing in such detail with a vital matter that was so often glossed over. He expressed the view that this new approach to the fabrication of supporting skirts had been very much appreciated by all those who had come to hear this most interesting paper. B.K.B.

CONTRIBUTORS TO THE JOURNAL

J. A. Donelan, A.M.Inst.W., is a member of the senior scientific staff of the Research Laboratories of the General Electric Co. Ltd. at Wembley. After receiving his technical education at the Willesden and the Regent Street Polytechnics, he joined the Company in 1939, and is now engaged on the development of welding processes and techniques. Mr. Donelan is a member of welding committees of the British Standards Institution and of the Electrical Research Association.

E. Holmes, M.A., Ph.D., a Lecturer in the Department of Metallurgy at Nottingham University, graduated from Cambridge University in 1947 with a Bachelor's degree, and gained his M.A. in 1957. He joined the

J. A. Donelan

E. Holmes

L. G. Johnson

D. James

J. Sawkill

Witton Works of I.C.I. in 1948, and was there concerned mainly with problems associated with the joining of non-ferrous alloys.

In 1952 Dr. Holmes became a senior member of the ply-metals research team in the University of Birmingham Department of Industrial Metallurgy, his work there resulting in the conferment of a Ph.D. degree. He took up his present appointment in 1955, his main interests being in the field of pressure welding and the non-destructive testing of welds.

L. G. Johnson, M.A., A.M.I.Struct.E., General Manager of the Skeleton Steel Co. Ltd., Stratford-on-Avon. He was educated at Blackpool Grammar School and at Emmanuel College, Cambridge, where he took Part 2 of the Mechanical Sciences tripos in 1947. After a brief period with S. & C. Walmsley of Aintree, Mr. Johnson joined the Bridge and Constructional Department of Dorman, Long & Co. Ltd. in Middlesbrough.

In 1953 he was appointed chief draughtsman of Sidney Raines Ltd., constructional engineers of Wakefield, and two years later he became senior assistant in research at the Department of Engineering of Cambridge University. He was promoted to Assistant Director of Research in 1957, but resigned a year later to take up his present appointment.

D. R. Jackson, A.I.M., Assistant Metallurgist with the British Aluminium Co. Ltd., was born in 1929. He first joined the Company in 1945, and worked in various departments of the Research Laboratories, including the experimental foundry, structural engineering, and the physics laboratories.

During his period of National Service, from 1947 to 1949, Mr. Jackson was a radar mechanic in the Royal Air Force. He took up his present position in the Experimental Department of the Latchford Locks Works of the Company in 1957, and is now engaged on general quality control, and extrusion and casting problems associated with aluminium. After attending part-time courses at the Battersea Polytechnic, Mr. Jackson qualified by examination for Associateship of the Institution of Metallurgists in 1955.

D. James, M.A., in charge of technical development at Tube Investments Ltd. and with Reynolds T.I. Aluminium Ltd.

After obtaining his degree at Cambridge University, Mr. James served an apprenticeship with the Aluminum Company of America. He was then transferred to the Northern Aluminium Co. in London, where he was engaged in sales engineering for some years. Mr. James joined Baker Platinum Ltd. in 1937, and during the war years, apart from general administrative duties, he was responsible for research in the production of sintered platinum alloys to meet Ministry of Aircraft needs. He took up his present appointment in 1954.

J. Sawkill, Ph.D., Head of the Metallurgy Section at the Tube Investments Research Laboratories, Hinxton Hall, Cambridge. He was educated at West Hartlepool Grammar School and at King's College, Newcastle-on-Tyne, where he was awarded his degree in 1951.

Dr. Sawkill then spent two years in the post-graduate school of Physical Metallurgy at Sheffield University and a further two years in the Research Laboratory for the Physics and Chemistry of Surfaces at Cambridge University. He took up his present appointment in 1955.

INTERNATIONAL INSTITUTE OF WELDING

The Annual Assembly of the IIW for 1959 will be held at Opatija, Yugoslavia, by invitation of the Yugoslavian Delegation. The meeting will commence on 27th June and will continue to 4th July.

The programme follows the usual pattern, a meeting of the Executive Council being held on the first day, with a meeting of the Governing Council on the following day. The Public Session for the reading of papers on 'Welding and Allied Processes (Gas Cutting, Building-up, Bronze Welding, Surface Hardening, Metal Spraying) in Maintenance and Repair Work' will be held on Monday 29th June.

The meetings of Commissions will occupy the four following days, and the closing meeting of the Governing Council and Executive Council will be held on Saturday, 4th July. As usual, a number of tours is to be arranged for the following week.

Notices of the Programme will be sent to members of the British Delegation early in 1959.

NEWS FROM INDUSTRY

Instrumentation and computation

A Joint Symposium on *Instrumentation and Computation in Process Development and Plant Design*, organized by The Institution of Chemical Engineers, the Society of Instrument Technology, and The British Computor Society, under the aegis of the British Conference on Automation and Computation, is to be held in London on 11th–13th May 1959.

A preliminary programme and further details may be obtained from: The General Secretary, The Institution of Chemical Engineers, 16 Belgrave Square, London, S.W.1.

Welding exhibition

The Engineering, Marine, Welding, and Nuclear Energy Exhibition, traditionally held in the autumn in alternate years, has this time been rearranged to open in the spring of 1959, from 16th to 30th April.

Members of the Institute will know that the annual Spring Meeting has been arranged to coincide partly with the period of the Exhibition.

There will be more than 1000 categories of engineering products and plant on show, and the exhibits will occupy the three Olympia halls.

Brief information on the welding exhibits will be given in later issues of the Journal. Detailed information on the Exhibition as a whole should be obtained from the Organizers, F. W. Bridges & Sons Ltd., Grand Buildings, Trafalgar Square, London, W.C.2.

Welding information centre

An information centre has been established by the American Welding Society, in New York City, U.S.A., for the dissemination of welding news and information. The centre will act as an authoritative source for information relating to the weldin industry, except for products, equipment, and personnel, which are regarded as company matters.

New general purpose electrode

A new electrode in the Rockweld range for welding mild steel, the V117, can be

used for a variety of applications. Its characteristics are stated to compare favourably with the more specific types, and in some instances its qualities are superior.

The V117 is easy to use in any position, and it has excellent slag control. It deposits as well in the overhead position as in the vertical, and easy slag removal from deep grooves is an important feature. The electrode has received the approval of the Ministry of Transport, and of Lloyd's Register of Shipping, and it conforms to the requirements of various British Standards concerned with the welding of mild and medium high-tensile steels.

Electron-beam welding

Equipment for development and research into electron-beam welding is now being made in Britain by Edwards High Vacuum Ltd., under licence to British Patent Application 1962/57.

This technique for welding reactive metals has been developed at the Commissariat a l'Energie Atomique, Saclay, France, and was described in a paper by J. A. Stohr and J. Briola presented to the Vienna Assembly of the IIW in 1958.

The apparatus will be on show at the Company's stand at the 43rd Annual Exhibition of the Physical Society, from 19th to 22nd January.

Double ended flash butt welder

A fully automatic double ended flash butt welding machine, designed for application to workpieces comprising three components, and where the main part has a smaller part joined at each end, has been recently introduced by A.I. Electric Welding Machines Ltd.

A typical application is the welding of tractor links, where forged link eye bars are simultaneously welded to each end of a central link produced from bar stock. The machine has a central fixed hydraulic clamp and two transverse sliding heads to provide the clamping and upsetting pressure. There is an automatic preheating system, and the main controls are operated by push buttons. At the completion of welding all the clamps release and the sliding units return automatically to the loading position.

Tractor links being joined in a double-ended flash butt welder.

Portable welding transformer

There are many inherent advantages in a relatively lightweight power source for a.c. welding in the medium current range. Many of them appear to be provided in a new transformer recently put on the market by Portable Welders Ltd.

The new Fararc 200 is a fan-cooled toroidal transformer, weighing 70 lb and measuring 14 in. cube. The output can be varied, with 36 current settings, between 60 and 230 amp, with a maximum continuous rating of 200 amp. The equipment has a high power factor, 0·8–0·9 lagging, and may be connected direct to a 200/250 V or 400/440 V a.c. mains supply.

The open-circuit voltage is 50, which provides greater safety for the operator, and a reduction of load on the supply. The transformer can be operated without damage at temperatures up to 180°C., but should there be accidental overheating an automatic switch cuts off the welding current but not the cooling fan. The Company are to produce a junction box that will allow the coupling of sets to provide 400, 600, or 800 amp.

DIARY

5th Jan.—**Sheffield**—Annual Dinner (Royal Victoria Hotel).

6th Jan.—**South Western**—*Metal Spraying* by G. Payne (Radiant House, Bristol).

7th Jan.—**Manchester**—*Fabrication of Stainless Steel* by B. Banks (College of Science and Technology).

8th Jan.—**South London**—*Practical Significance of BWRA Work on Gas Shielded Welding Processes* by A. A. Smith (54 Princes Gate, 7.30 p.m.)
North Eastern (Tyneside)—*Welding from the Viewpoint of Lloyd's Register* by G. M. Boyd.

8th–9th Jan.—British Society of Rheology—Conference of *Behaviour of Metals at Low and High Temperatures* (Leeds University).

12th Jan.—**Sheffield**—Talk and Film on the *Jodrell Bank Telescope* by C. N. Kingston. Joint meeting with Rotherham Eng. Soc. (Rotherham Technical College, 7.15 p.m.)

13th Jan.—**Liverpool**—*Inspection of Welding* by D. T. Carter (College of Technology, Byrom Street).

15th Jan.—**Southern Counties**—*Some Aspects of Welding Inspection* by C. C. Bates (Southampton).

16th Jan.—**Birmingham**—*Importance of Welding Research for Industry* by R. Weck.

20th Jan.—**Eastern Counties**—*Plastic Theory of Structures* by T. M. Charlton (Electric House, Ipswich, 7.30 p.m.)

21st Jan.—**North Eastern (Tees-Side)**—*Heat Exchangers* by A. R. Muir.
Wolverhampton—*Resistance Welding and Brazing in Light Engineering* by E. V. Beatson (Holybush Hotel, 7.30 p.m.)
West of Scotland—*Making Electrodes* by D. C. Cotton.
Leeds—*Manufacture of a Fusion Welded Pressure Vessel* by W. Weightman (Gt. Northern Hotel, Leeds, 7.30 p.m.)

22nd Jan.—**East Midlands**—*General Considerations in Welding Materials for Industrial and Chemical Plant* by M. Birkhead (College of Art, Derby, 7.15 p.m.)

28th Jan.—**South London (Medway Section)**—Argonarc Welding Demonstration (Medway College of Technology, Chatham, 7.30 p.m.)
North London—*Materials and Fabrication Problems in Reactor Technology* by A. Prince (54 Princes Gate, 7.30 p.m.)

2nd Feb.—**West Wales**—*Recent Thoughts on Structural Welding* by A. V. Hooker (Swansea Technical College).
Manchester—*Weld Inspection* by D. T. Carter (College of Science and Technology).

3rd Feb.—**East Wales**—*Modernisation of British Railways* by M. G. R. Smith and R. A. Smeddle (as presented to S. W. Inst. Eng. Cardiff on 24th April 1958). (S.W. Inst. Eng., Cardiff.)
East Midlands—*Weldability of ND Steels* by L. Reeve (Welbeck Hotel, Nottingham, 7.15 p.m.)

5th Feb.—**Eastern Counties**—*Metal Spraying Techniques* by Mr. Shepherd (Norwich City College, 7.30 p.m.)
North Eastern (Tyneside)—*Planning for Welding in Shipbuilding* by P. H. H. Rhodes.

6th Feb.—**South Western**—*Gas Cutting and Welding* by L. B. Smith (Radiant House, Bristol, 7.15 p.m.)

CORRECTION

An unfortunate transposition of wording in part of the *Presidential Address* (December 1958 issue of the *Journal*) has made nonsense of one sentence as printed:

p. 547, left col., 4th para., 2nd sentence, should be altered to read:

"Even ignoring individual variations, the processes include: manual covered-electrode welding; automatic and semi-automatic . . . etc."

APPOINTMENTS

Situations vacant

Chemist required by old-established electrode manufacturing company, for electrode control and development. Details of experience and salary required to Box 225.

Welding Engineer, age 25 to 35, required by leading manufacturers of manual and automatic arc welding plant and electrodes for senior post in the Technical Sales Department. A wide knowledge of welding processes and a keen and enthusiastic interest in technical sales promotion is essential.
Degree or equivalent qualification preferred. Box No. 226.

The cost of insertions in this column is 3*s.* 6*d.* a line, or 30*s.* per inch depth semi-display.

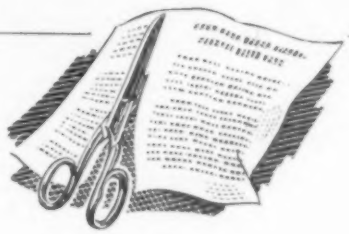
Box numbers are added for the additional charge of 2*s.* 6*d.* Replies should be addressed to Box — , Institute of Welding, 54 Princes Gate, London, S.W.7.

All other matters relating to advertisements for this section of the News should be addressed to the Executive Editor, 6 Ridge End, Hook Hill Lane, Woking, Surrey (Tel. Woking 2981).

Copy should be sent by 6th of each month for publication in the following month.

Current WELDING LITERATURE

Book Reviews
Additions to the Institute Library
Trade Publications



CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Australian Welding Journal, 1958, vol. 1, August

The manufacture and application of an open arc automatic welder, J. L. Young (11–13)

Inert gas automatic welding equipment, I. W. McGeachie (16–18)

Gas shielded welding of structural grade carbon steel, R. A. Stringer (19–23)

Inert gas welding of steel pressure vessels, T. Boyle (26–27)

Estimating quantities in a welding shop, B. Osman (32–35)

Tooling for efficient welding, C. M. Smith (42–45)

Journal of the Japan Welding Society, 1958, vol. 27, August

Theory of brittle fracture, Pt. 2, M. Otani (3–8)

Stainless steel overlays on mild steel, Report 1, T. Nannichi (9–13)

Wear resistance improvement of spot welding electrode, S. Onimaru and H. Shomoto (14–19)

Remote control method of AC welding machine, 2nd method, E. Segihara and S. Kikuchi (20–22)

On the porosity of weld steel with low hydrogen type electrode, Report 1, H. Sekiguchi, I. Masumoto, and H. Oda (23–28)

Melting electrode wire in Mig arc transfer of metal drops, Report 3, A. Uchida (29–34)

Cooling time and brittleness of various steels submitted to welding, Reports 1–2, H. Sekiguchi and M. Inagaki (35–43)

Physical properties of welding slags, K. Okada and T. Fukaya (44–50)

Przeglad Spawalnictwa (Poland), 1958, vol. 10, October

Standardization of weldments evaluation on the basis of radiographic inspection, Pt. 1, M. Radwan and A. Fabiszewski

On the allowable stresses and safety factor for butt welds, Z. Mendera

Some results of fatigue tests of welded joints and elements, T. Robakowski

Schweissen und Schneiden (Germany), 1958, vol. 10, September

A new method for proving the existence of internal stresses caused by welding, W. Rädeker (351–358)

Investigations into the electro-slag process, R. Muller (359–367)

New knowledge and experiences gained in connection with cutting by oxygen, H. G. Kluge (368–373)

Self-starting welding generator sets with constant voltage, for use with railway and mining grids, K. Schydlo (374–376)

New developments in the field of radiography and the intensification of radiographs, H. Nassenstein (376–379)

Welding Engineer (U.S.A.), 1958, vol. 43, September

Braze welding saves an anvil, R. L. Rectenwald (38–39)

Engineering data sheet No. 216—Corrosion properties of titanium, zirconium, tantalum and Type 316 Stainless steel (41)

Proper shielding—sound welds (in welding titanium) (40, 42–43)

The fundamentals of welding engineering, T. B. Jefferson (44–46)

Welding satisfies rigid chemical industry criteria, R. Utnehmer (48)

Shift to welded joints for small diameter pipe, H. A. Sosnin (52–53)

Unit roofs are welded to columns (57)

Welding Journal (U.S.A.), 1958, vol. 37, October

Welding cast components for nuclear-power applications, W. H. Rice (971–978)

Welding low-alloy steel castings for high-pressure and high-temperature service, N. A. Chapin, C. H. Soldan, and L. W. Songer (979–987)

Automatic line tracing in oxygen shape-cutting machines, A. F. Chouniard and E. L. McDonald (988–990)

Welding qualification and component performance, W. L. Fleischmann (991–996)

Cupro-nickel welding with aluminium bronze, discussion by J. Imperati, F. L. Laque, and L. H. Hawthorne, closed by author –V. Abaravich, of article on pp. 220–224 (997–1000)

The Atomium dramatizes welding, C. E. Jackson (1001–1003)

The acetylene flame in the piping industry, H. A. Sosnin (1004–1005)

Precision plus, J. J. View and C. W. Pfleiger (1006–1007)

Hard surfacing paste aids production of abrasion-resistant surfaces, L. V. Larou (1008–1009)

Hard surfacing in field and shop keep slag-recovery operation going, R. Haas (1010–1011)

Residual stresses in welded titanium plates, E. F. Nippes and W. F. Savage (433s–439s)

Welding of molybdenum-alloy sheet, K. M. Kulju and W. H. Kearns (440s–444s)

Correlation of metallurgical properties and service performance of steel plates from fractured ships, M. L. Williams (445s–453s)

Advances in welding austenitic materials in the construction of chemical apparatus and tanks, J. Mundt (454s–467s)

Toughness of welds evaluated separately and in composite, W. P. Hatch and C. E. Hartbower (455s–462s)

Studies of stress-corrosion cracking of austenitic stainless steel, H. L. Logan (463s–467s)

Corrosion of Zircaloy-2 sheet weldments, R. Stein and R. E. Monroe (468s–472s)

Static brittle-fracture initiation at net stress 40% of yield, C. Mylonas, D. C. Drucker, and J. D. Brunton (473s–479s)

University research work, W. Spraragen (480s)

Welding and Metal Fabrication, 1958, vol. 26, October

The Marchon fabrication shop; extensive use of welding at a famous chemical works, D. M. Potter (350–357)

Zirconium, F. G. Fox (358–365)

Vacuum welding of metals, J. A. Stohr and J. Briola (366–370)

Kingsferry bridge (371–374)

Practical aspects of automatic welding, J. A. Lucey (375–380)

Welding News (*Australia*), 1958, Folio 95

Oxy-acetylene aids Rheem production line (2–3)

Flame cleaning finds wide acceptance (4–5)

Dual coating, a new technique in electrode manufacture (6–7)

Argonaut welding of stainless steel (8–9)

Braze welding (11–13)

Pipe cutting and peak performances (15)

Welding News (Holland), 1958, No. 90, April

The Adma enterprise, P. J. Carberry (2–5)

Stud welding with Philips stud gun, C. E. H. Price (6–9)

Welding News (Holland), 1958, No. 91, May

The Philips CO_2 automatic welding method, J. Camerlick (2–8)

Welding News (Holland), 1958, No. 92, June

The French pavilion at the Brussels Universal exhibition 1958, G. van Schiack Sillesen (2–9)

Welding Production (U.S.S.R.), 1958, October

New fluxes for arc welding, K. V. Lubavsky and E. P. Lvova (1–5)

Iron-nickel electrodes for cold welding of high-strength and grey cast iron, G. N. Larin, V. V. Bazhenov, and L. M. Yarovinsky (5–8)

Mechanical properties and weldability of Bessemer vacuum treated steel, A. I. Krasovsky and V. D. Kodolov (8–11)

Weldability of oxygen melted converter steel, A. S. Astafyev (12–14)

Effect of boron on the tendency of Type 1X13H18B2Б heat-resisting austenite steels to form hot cracks on welding, A. V. Russyan and M. K. Shorshorov (14–18)

New method of welding by electrical rivet fusing, A. Y. Brodsky (18–21)

Electroslag welding of 20ГС steel, V. M. Seminov (21–23)

Features of welding the first layer of gas turbine rotor butt seams, V. A. Toropov (24–26)

Precision automatic arc welding of non-fusing electrode in a hydrogen atmosphere, F. I. Kisluk, V. V. Gorbansky, and A. F. Khudyshev (26–29)

Other Journals

Automatic electrical welding of cathode ray tubes (*Engineering*, 1958, vol. 186, October 24, pp. 554–555)

Electric arc welding with high duty electrodes, E. Kauhausen, P. Kaesmacher, and F. J. Adamski (*Werkstatt und Betrieb*, 1958, vol. 91, October, pp. 597–603)

Automatic welding: some considerations on its use, I. C. Fitch (*Metropolitan-Vickers Gazette*, 1958, vol. 29, October, pp. 265–273)

Gas shielded self adjusting arc welding as applied to steels—2, H. Levinsohn (*New Zealand Engineering*, 1958, vol. 13, August 15, pp. 307–310)

The use of arc welding in structural engineering, J. S. Allen (*The Structural Engineer*, 1958, vol. 36, October, pp. 334–344)

Special spot welding methods (*The Brown Boveri Review*, 1958, vol. 45, May, pp. 223–235)

How to service resistance welders, Pt. 2: Periodic welder inspection procedure (*Machine Production* (Canada), 1958, vol. 17, September, pp. 28–30, 68)

Design factors in silver brazing, L. D. Connell (*Engineering Materials and Design*, 1958, vol. 1, November, pp. 96–98)

Boost powder metal part size. Join sections with silver solder, R. H. Weichsel and E. T. Johnson (*The Iron Age* (U.S.A.), 1958, vol. 182, October 2, pp. 80–81)

Sheet metal welding; a report of three papers presented to a meeting of the North London Branch of the Institute of Welding: Resistance welding, C. A. Burton; **Inert-gas welding,** F. H. Chaffer; **Automatic submerged arc welding,** F. W. Pinkstone (*Sheet Metal Industries*, 1958, vol. 35, October, pp. 755–766)

Dip brazing of Aluminium pays with accurate assemblies, E. G. Slotta (*The Iron Age*, 1958, vol. 182, September 25, pp. 92–93)

Non-destructive testing, Pt. 3—use of dye and fluorescent penetrants: auxiliary equipment for local examination (*Aircraft Production*, 1958, vol. 20, November, pp. 420–431)

How design can effect the fatigue of welded structures, T. R. Gurney (*Engineering Materials and Design*, 1958, vol. 1, November, pp. 72–75)

Stainless Steel as a structural material, I. L. G. Baillie (*Engineering Materials and Design*, 1958, vol. 1, November, pp. 92–95)

Welder trims furnace cost (*Steel* (U.S.A.), 1958, vol. 143, September 29, p. 100)

How a welded frame machine design met a vibration problem, R. J. Gillespie (*Canadian Machinery*, 1958, vol. 69, September, pp. 136–139)

Uses grow for ceramic coatings, F. D. Shaw (*The Iron Age*, (U.S.A.), 1958, vol. 182, September 25, pp. 94–95)

Application and heat treatment of plain and alloyed steels, A. G. Gardner (*Mechanical World*, 1958, vol. 138, October, pp. 438–442)

Subzero welding in the Antarctic, David Pratt (*Torch*, 1958, No. 18)

Positioners and manipulators, S. G. Maine (*Engineer and Foundryman*, (S. Africa), 1958, vol. 24, August, pp. 48–52)

Which clamps are best for jigs and fixtures?, F. Strasser (*The Iron Age* (U.S.A.), 1958, vol. 182, October 2, pp. 84–87)

ADDITIONS TO THE LIBRARY

BOOKS AND PAMPHLETS

BRITISH STANDARDS INSTITUTION. BS. 1510:1958. *Steels for use in the chemical, petroleum and allied industries.* Low temperature supplementary requirements to BS. 1501–1506. This

standard has been prepared as part of a comprehensive scheme of codes for pressure vessels for use in the chemical and allied industries. These supplementary requirements cover temperatures down to —190 C. Care has been taken to ensure that there is no conflict between these requirements and those specified in BS. 2762 'Notch ductile steels for general engineering purposes' and as far as comparable quantities are concerned, the requirements are the same. (Price 4*s* 6*d*)

BS. 1501–1506:1958. *Steels for use in the chemical petroleum and allied industries.* The edition of 1950 has been superseded by this new series, part of a comprehensive scheme of codes for pressure vessels for use in the chemical and allied industries, covering also plates, bars and sections, forgings, castings, and bars for bolting material. Indicated are the nearest American equivalent steel in either the A.S.T.M. or the A.I.S.I. series. (Price 25*s*)

BS. 3014:1958. *'As welded' and cold drawn welded austenitic stainless steel tubes for mechanical, structural and general engineering purposes.*
This standard has been prepared under the authority of the Iron and Steel Industry Standards Committee and is one of a series of British Standards for steel tubes for general engineering purposes. (Price 4*s* 6*d*)

Copies of these Standards may be obtained from the British Standards Institution, London.

Aluminium windows, September 1958. The Aluminium Development Association, London. (Price 10*s* 6*d*)

Platinum Metals Review, vol. 2, October 1958, No. 4, Johnson, Matthey & Company, London.

BRITISH WELDING RESEARCH ASSOCIATION. *Interim report on CO_2 shielding of metallic arc welding of aircraft steels and alloys combined with the use of C.P. welding generators*, September 1958. Prepared by B.W.R.A. under Ministry of Supply contract 6/Aircraft/13832/CB 6(b). Ministry of Supply Technical Information and library services, London.

42nd Annual report of the Executive Committee for the year ending 28 February 1958. The National Central Library, London.

37th Annual report for the year ending June 30th, 1958. The British Cast Iron Research Association, Birmingham.

Design and operation of low pressure acetylene generators. The British Acetylene Association, 1958, London. (Price 7*s* 6*d*)

N. H. JONES, *Factories Acts 1937 and 1948; a concise summary applicable to Iron and Steel works, 1958.* The United Steel Companies Limited, Sheffield.

An account of the central organisation in the steel industry, 1958. The British Iron and Steel Federation, London.

Titanium welding techniques. (Titanium engineering bulletin No. 6), 1958. Titanium metals corporation of America, New York.

Rules and regulations for the construction and classification of steel ships, Notice No. 2120. 1958. Lloyd's Register of Shipping, London.

UNITED NATIONS. INDUSTRIAL DEVELOPMENT DIVISION. *Problems of the steel making and transforming industries in Latin America. 1. Report of the Latin American meeting of experts on steel making and transforming industries.* 1958, United Nations, New York (Price 5*s*.).

Wiggin nickel alloys in aircraft. 1958; *Corrosion-resisting characteristics of Wiggin high-nickel alloys.* May 1958; *Corrosion in the petroleum industry.* 1958, by Professor F. H. Garner and Dr. A. R. Hale; *The engineering properties of Monel, Nickel, Inconel.* 1958, Henry Wiggin & Co. Ltd., Birmingham (Free on request).

TRADE CATALOGUES

"Puma" diesel-electric generating sets. 1958, Grahame Puttick Limited, Ash, Kent.

Electric resistance welding; the way to increased productivity and lower costs. 1956, The British Electrical and Allied Manufacturers' Association, London

"Endewrance" high alloy castings; "Endewrance" hard facing welding rods. 1956, Dewrance & Company Limited, London.

Welding in the Chemical Industry

Many of the papers presented at the Public Session of the Vienna Assembly of the International Institute of Welding have been or will be published in the technical periodicals of the countries of origin. But it is considered to be useful to present a record in the JOURNAL *of the English titles and synopses of these papers.*

At the time of going to press the published sources of most of the papers were not known. They are, however, given for reference where possible.

Typical Examples of Welded Constructions for the Chemical Industry. Takeo Naka, Akira Tsuruta, Yoshio Sakai, Keizo Tezuka, and Toshie Okumura.

Progress in the chemical industry, especially the latest developments in the petroleum, artificial fibre, and pulp industries, has increased the severity of operating conditions, resulting in a demand for special welding techniques. The paper describes the problems which have been dealt with in a number of applications.

Present Status of Welding Engineering in the Japanese Chemical Industry. Takeo Maka, Akira Tsuruta, Yoshio Sakai, Keizo Tezuka, and Toshie Okumura.

In recent years there has been a great increase in the use of welding in the construction of chemical plant made of stainless and Cr-Mo steels, aluminium, titanium, copper alloys and other metals. The paper describes the present situation in Japan, and makes particular reference to the welding of spheres.

Selected Examples of Welded Structures in Chemical Engineering, Rudolf Soehngen. (*Schweissen u Schneiden*, 1958, vol. 10, pp. 260–265)

Because of its adaptability in design and in respect of the materials used, welding in chemical engineering allows, technically and economically, an optimum solution to the problems that arise. Welding therefore plays a large part in the styling of apparatus. After describing the special problems of chemical engineering, the paper emphasizes the requirements that have to be met by a weld. Some design examples are illustrated, starting with such basic items as flanges, nozzles, and tube welds in heat exchangers. Particular reference is made to the need for meeting anti-corrosion requirements.

Construction of Large Welded Processing Equipment for the Chemical Industry. Tebaldo Cavallucci and P. I. Nino Argenti.

The construction of three large pieces of equipment for the chemical industry—reactors for synthetic rubber manufacture

coolers in stainless steel, and propane storage tanks—is briefly described. Information is also given about the different technological processes used.

Application of Welding to the Construction of Chemical Apparatus. Paul Richter. (*Schweissen u Schneiden*, 1958, vol. 10, pp. 265–269)

The paper describes in detail the special welding techniques developed for joining thick-walled parts, heavy tops and bottoms, and the connections of pipework to chemical apparatus. There is also a section dealing with hard-facing and building up by welding.

Contribution to the Design and Calculation of Welded Hollow Vessels for Operation at High Temperatures and Pressures. Albert F. Maier. (*Schweissen u Schneiden*, 1958, vol. 10, pp. 270–276)

The author discusses the distribution of stress, deformation, and breaking strength in fabricated heavy welded vessels. On the basis of previous experiments he indicates the factors to be considered in the design of highly-stressed interior tubes, and demonstrates the basic calculations for two types of hollow high-pressure vessels.

Welding at the Lacq Gas Field, P. Berthier, R. Enous, J. Souviron, R. Terminet, and G. Reynes.

The recently discovered Lacq field probably constitutes the largest area of natural gas in Europe. The offensive and poisonous nature of the gas, coupled with the high operating temperatures and pressures, have produced considerable problems in extraction, transportation, and treatment. The welding of the mild steel pipes of the collecting network has been carried out and inspected with particular care; for example, all assemblies are stress-relieved. The gas washing towers are fabricated from 0·3%C steel and the lower sections are lined with 3 mm thick Cr-Ni-Mo steel. The machinery and pipes of the recovery plant, carrying the purified gas, have not presented any special problems.

Welding of Equipment at the Marcoule Plutonium Extraction Plant. Pierre Couturier. (*Soudage Techn. Connexes*, 1958, vol. 12, pp. 277–287)

A considerable amount of stainless steel was needed for the construction of the works for the extraction of plutonium, undertaken for the Marcoule Atomic Industrial Centre by Manufactures de Glaces et Produits Chimiques Saint-Gobain, Chauny et Cirey. One of the greatest difficulties was the development of suitable welding procedures to produce welds that would resist the effects of corrosive products, particularly in inaccessible areas. Although the plant has been put into operation so recently that no concrete results can be reported it seems that the various tests and inspection carried out have ensured satisfactory welded assemblies.

Special Welding Problems in Nuclear Engineering. A. Lüthy.

Although the making of welds in pressure vessels and pipes of mild or low-alloy steel presents no fundamental problems, there is more uncertainty about welding high-alloy steels and other alloys whose weldability is questionable. The report deals firstly with normal welds in pressure vessels and pipes, and then examines some special examples in nuclear engineering, where the execution of pressure-tight welds presented certain problems. The discussion is illustrated by sketches and photographs of welds used in the fabrication of a power reactor.

Vacuum Welding of Metals. J. A. Stohr and J. Briola. (*Soudages Tech. Connexes*, 1958, vol. 12, pp. 165–172)

A new welding process has been developed by the Commissariat a l'Energie Atomique in France, in which the edges of the workpiece are melted by the impact of an electron beam. Welding is done in a vacuum of 10^{-4} to 10^{-6} mm of mercury. The welding equipment consists essentially of a metal enclosure in which a vacuum is produced; a cathode for electron emission, with a high-voltage generator for acceleration, and a focussing device; a mechanical device for moving or rotating the workpiece. The process has particular advantages for the welding of highly oxidizable metals, such as zirconium, the fabrication of high-vacuum-sealed metal containers, and the production of very deeply penetrated welds.

Welding of Nickel and High-Nickel Alloys in the Chemical Industry. J. Hinde. (*Brit. Welding J.*, 1958, vol. 5, pp. 311–318)

Wrought nickel and the high-nickel alloys find many uses in the chemical industry. The paper reviews their major applications, and considers the metallurgical and practical aspects of the materials, with particular reference to the corrosion resistance of the welded joint. The welding technique needed for maintaining the continuity of cladding is described for steels clad with nickel or high-nickel alloys. The method of strip-lining of vessels and the use of overlay techniques as a means of economizing in the use of materials is also considered.

Welding of High-Nickel Alloys for Chemical Plant and Equipment. R. P. Culbertson and R. C. Perriton.

The welding characteristics of four nickel-base alloys used in fabricating chemical plant and equipment are discussed, and the recommended practice to produce welds with optimum corrosion resistance is described. Three of the alloys are available in wrought form. The techniques for shop and site welding of lined and solid constructions are considered, and welding methods used for castings in the four alloys are described. Examples are given of cast and wrought welded equipment.

Determination of the Weldability of Steels for the Chemical Industry. Alois Zapletálek.

The paper describes some tests carried out to determine the weldability of certain types of steel and to establish suitable welding techniques. In addition to the results obtained on steels with medium chromium contents some information is given on investigations of the brittleness of austenitic types of steel at high temperatures.

New Methods for Welding Clad Steels. Josef Čabelka.

The weldability of stainless steels in general is treated in the first part of the paper, which then refers to weld cracking in the presence of 2–7% remnant ferrite. It is pointed out that the oxygen content of the steels plays a significant part in the reduction in impact strength, decrease in corrosion resistance, and weld cracking in fully austenitic steels. The effects of sigma phase are described, and again it is considered that oxygen is connected with the difficulties associated with this state. Reference is made to the Schaeffler diagram, and the paper ends with details of the cutting and welding of clad steels and the protection of joints against corrosion by the welding on of highly alloyed strips of material.

Some Aspects of Welding Stainless Clad Steel Cellulose Digesters. Goeran Almqvist and Erik Erikson.

The use of stainless clad steel as a structural material for cellulose digesters has become more common because of the corrosion problems associated with this equipment. The procedure for welding this material is discussed, and it is pointed out that the submerged-arc process produces sound welds for the base material. The paper describes the metallurgical conditions for successful welding and reports the laboratory tests on which the recommended procedures were based. The properties of the welds were studied by mechanical tests and by metallographical examination.

Metallurgical Conditions for Welding Clad Steel Plates. Wilhelm Raedeker. (*Schweissen u Schneiden*, 1958, vol. 10, pp. 255–259)

Welds in clad materials have to meet the requirements of both materials—mechanical resistance in the base metal, and corrosion resistance in the cladding. Yet to avoid cracking in the base-metal weld there must be no admixture of cladding material into this weld. The paper gives details of methods of obtaining high corrosion resistance for welds in cladding materials such as silver, copper, nickel, chromium steels, and austenitic chromium-nickel steels. Subsequent thermal treatment should be avoided, but if it must be used it should meet the properties of both layers of metal. In the stress-relief annealing of austenitic clad steels the temperature range at about 650°C. should be avoided.

Joining of Clad Metals and Lining Techniques. H. Gerbeaux.

The application of clad steel has been extended, owing to the use of welding, to a large range of sheet metal equipment. In France, clad steel fabrication is common practice, and it is possible to produce drawn tubes of clad steel. The advantages and limitations of clad steel as compared with solid constructions is outlined. Cutting procedures, joint preparation, welding methods, and stress conditions for various materials and types of assembly are dealt with. Strong linings and thin overlays for some apparatus are considered. It is suggested that with the increased use of clad materials suitable fabrication techniques should be introduced into relevant codes of practice.

Use and Application of Clad Steel, Metallic Liners, and Overlay Deposits in the Manufacture of Vessels for the Chemical Industry. L. Capel and C. Nederveen.

A review is given of the various applications of clad steel, metallic liners, and overlay deposits from the standpoint of the manufacture of apparatus in which these materials are used. The problems arising in welding are considered, with special reference to the difficulties arising from the dilution of stainless steel with unalloyed metal. A number of possible constructions are discussed in the light of the examples given.

Automatic Stainless Steel Overlay of Sulphate Digesters. F. Schneider and R. J. Walker.

The paper deals with the application of the inert-gas-shielded metal-arc (consumable wire) process for the automatic stainless steel overlaying of mild steel sulphate pulp digesters that have suffered corrosion to a point where the replacement of the digester or a reduction in the operating pressure is called for. As the dismantling of a digester is considered to be impractical, the overlay is applied to the digester wall in the vertical position. The development of the initial welding procedure, the application of an experimental test patch, and the complete overlaying of a digester are described.

Lining a Steel Pressure Vessel with Titanium. F. F. Ates.

The incorporation of a fixed titanium lining, 0·8 mm thick, into a steel pressure vessel is described. The vessel, about 80 cm dia. and 4 m long, was intended for use in the petrochemical industry at a working temperature of 140°C. and a pressure of about 8 atmospheres. The experience gained indicates that the lining of commercial sized pressure vessels with titanium is possible, using the well-established argonarc welding techniques and a suitable quality of titanium.

Welding Behaviour of Chemically Resistant Cr-Ni Steels of Higher Mo and Mo-Cu Contents. Alfred Schmidt.

The development of these steels has materially increased the possibilities in the construction of chemical apparatus, and a report on their welding behaviour is given in the paper. A special example of stress corrosion is illustrated. The behaviour of the steels with various welding processes is described, and the construction of a pickling vat of Mo-Cu alloyed Cr-Ni steel is mentioned.

Comparison between Low-Carbon Austenitic Stainless Steels and Stabilized Steels for Welded Chemical Apparatus. Börje Löfblad and Gunnar Lindh.

The paper describes investigations in which austenitic steels of the 18/8 type, with carbon contents varying between 0·03 and 0·14%, were compared with steels of corresponding compositions in which the carbon was stabilized with titanium. The steels were microscopically examined after heat-treatments in the range 650–750°C. Corrosion tests were also carried out. The results are discussed on the basis of another investigation in which the heating effect on the material during the welding process was studied. It appears that austenitic low-carbon steels with less than 0·06%C are fully comparable with titanium-stabilized steels, and in some respects they are superior.

Development of a Transition Weld between Ferritic and Austenitic Superheater Tubing for Steam Plant Application. Börje Löfblad and Gunnar Lindh.

A new method of making welded joints between ferritic and austenitic materials in superheater tubes is described, in which an intermediate piece of an alloy with a high nickel content is used. This alloy has a chromium content about the same as that of the ferritic material and its carbon is stabilized with niobium or some other suitable element. Tests have shown that the coefficient of thermal expansion for this insert alloy, in the range 20°–600°C., is midway between those for the ferritic and austenitic steels; for this reason there are smaller stresses in a joint made with this insert than in one made with a direct weld between the two materials. Microscopic examination of long-time annealed material shows that the nickel alloy prevents carbon diffusion from the ferritic steel. The paper also includes results of tensile tests at room temperature and stress-rupture tests at 600°C.

Evolution of the Hanford Technique for Inert-Gas Welding of Austenitic Stainless Steel Piping Systems. Eugene B. La Velle.

The extremely high quality of welding required at Hanford for installations of austenitic stainless steel pressure vessels and piping systems for conveying radioactive chemical solutions has necessitated an extensive examination of the known techniques concerned with the use of the inert-gas-shielded tungsten-arc process. The welding problems at Hanford are typical of those existing in the nuclear industry, and the methods used to obtain superior welds have resulted in a consistent improvement in fabrication. The various methods which have been used are evaluated according to economics, degree of skill needed, and the quality of the weld.

Welding of Cr-Mo Steel. Paul de Marneffe.

The fabrication of large parts of Cr-Mo air-hardening steel requiring considerable floor space poses very difficult problems of welding. The paper shows that the use of standard austenitic steel electrodes has already permitted the achievement of many practical applications, but that a particular electrode with a high nickel content has special advantages. It is considered that this electrode makes a much more homogeneous joint.

Flawless Welding of Austenitic Steel Castings. W. A. Stauffer and A. Keller.

Various methods have been proposed for the prevention of the transition zone cracking that occurs in the welding of austenitic steel castings. It is considered that the best way to overcome the difficulty is to peen the joint edges before welding. The tendency of the primary grain boundaries to cracks is thereby reduced, and during subsequent welding new grain growth occurs which avoids any cracking.

New Electrodes for Welding Thick Sheets. Jan Wegrzyn.

The paper describes the difficulties that arose during the development of copper electrodes for the manual arc welding of copper. It gives details of thick coated electrodes for manual arc welding of thick plates, and provides information on the mechanical and metallographical properties of welded joints in 20 mm thick copper plates.

Automatic Welding of Aluminium Plate. J. E. Tomlinson and D. Slater. (*Brit. Welding J.*, 1958, vol. 5, pp. 361–368)

The successful operation of automatic welding methods depends on a thorough understanding of the interaction of all process variables. Tests are described in which individual variations are studied and the results obtained are used to predict the welding conditions for the high-quality close square butt welding of plate up to ⅜ in. thick. Greater thicknesses cannot be welded in this manner owing to the welding current limitations of 400 amp imposed by existing equipment.

Powder Cutting in the Chemical Industry. Valentin Trunschitz.

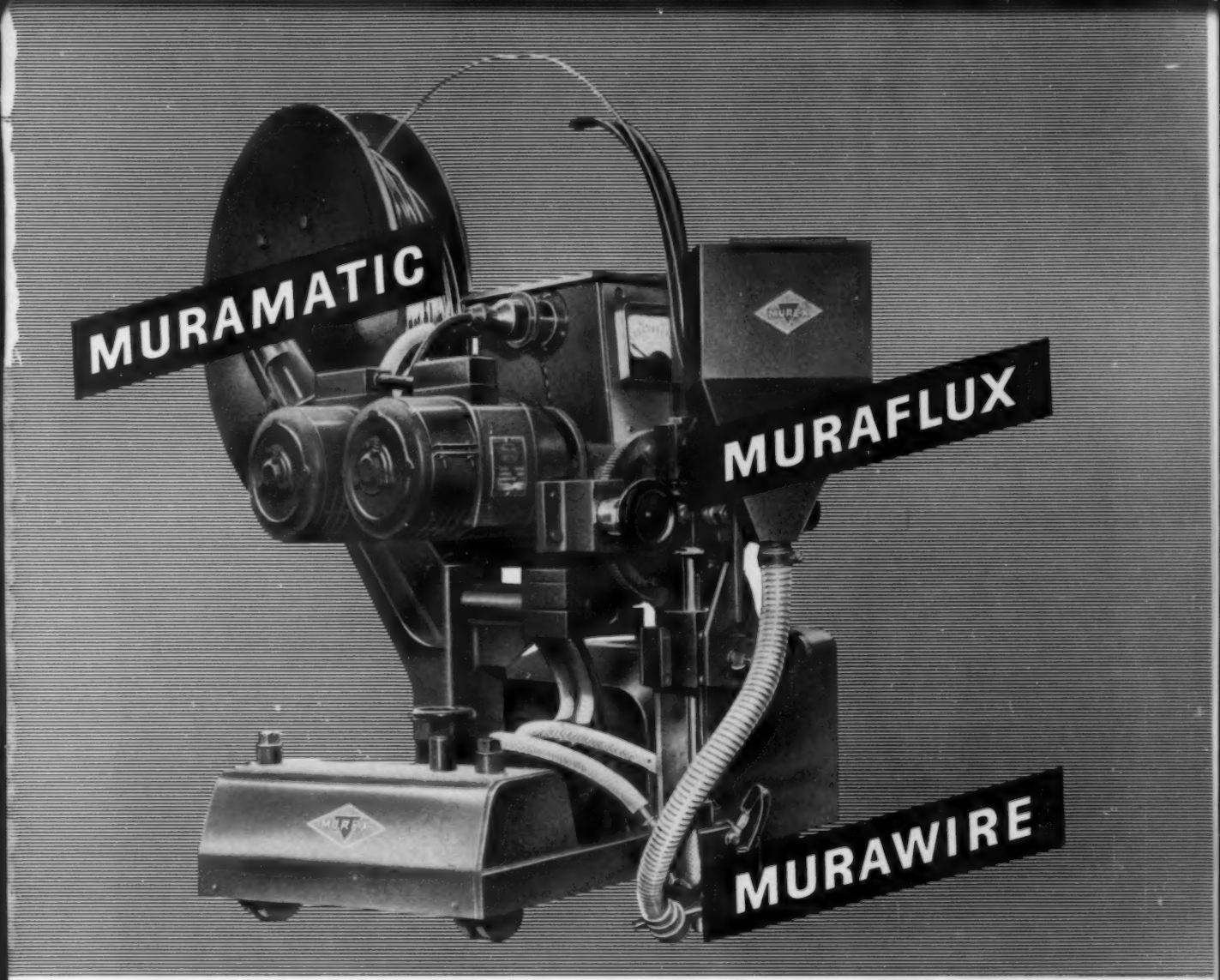
The paper deals with a practical method of investigating the effect of the power cutting process on the metallurgical changes in the area of the cutting edge subjected to heat. The materials used were a stabilized and a non-stabilized 18/8 Cr-Ni steel. A simple way of detecting the metallurgical changes is described from which the production engineer can decided what method of finishing—brushing, grinding, or milling—is needed, to prevent damage to the cut edges that would lead to corrosion.

Pulsating Pressure Fatigue Tests on Pressure Vessel Branch Connections. P. H. R. Lane. (*Brit. Welding J.*, 1958, vol. 5, pp. 327–332)

The paper describes a limited investigation of the behaviour of model pressure vessels (20 in. dia., 1 in. thick) subjected to pulsating internal pressure. Each vessel was provided with one branch, and the object of the tests was to compare four different welding details used for attaching the branches to the shells. Two of the joint details had interpenetrating welds made from the inside and outside of the shell, and two had inner and outer welds which did not fully penetrate the shell thickness. Examination of the fractures showed that the root area of the welds in the latter designs was not a source of weakness.

Effect of Welding and Stress Relief on the Parent Plate. J. E. Roberts. (*Brit. Welding J.*, 1959, vol. 6)

The mechanical properties of the heat-affected zone of a welded plate are shown to be equal to those of the parent plate, provided that cracking, or excessive hardening that might lead to cracking, is absent. This applies to mild steel, notch ductile steels, and low-alloy high-strength weldable steels. Initiation of brittle fracture in a welded structure is shown to be highly dependent on the presence of residual stresses, though the use of notch ductile steels considerably reduces the risk of such fractures, even in the presence of residual stresses.



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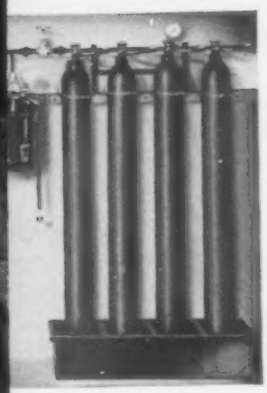

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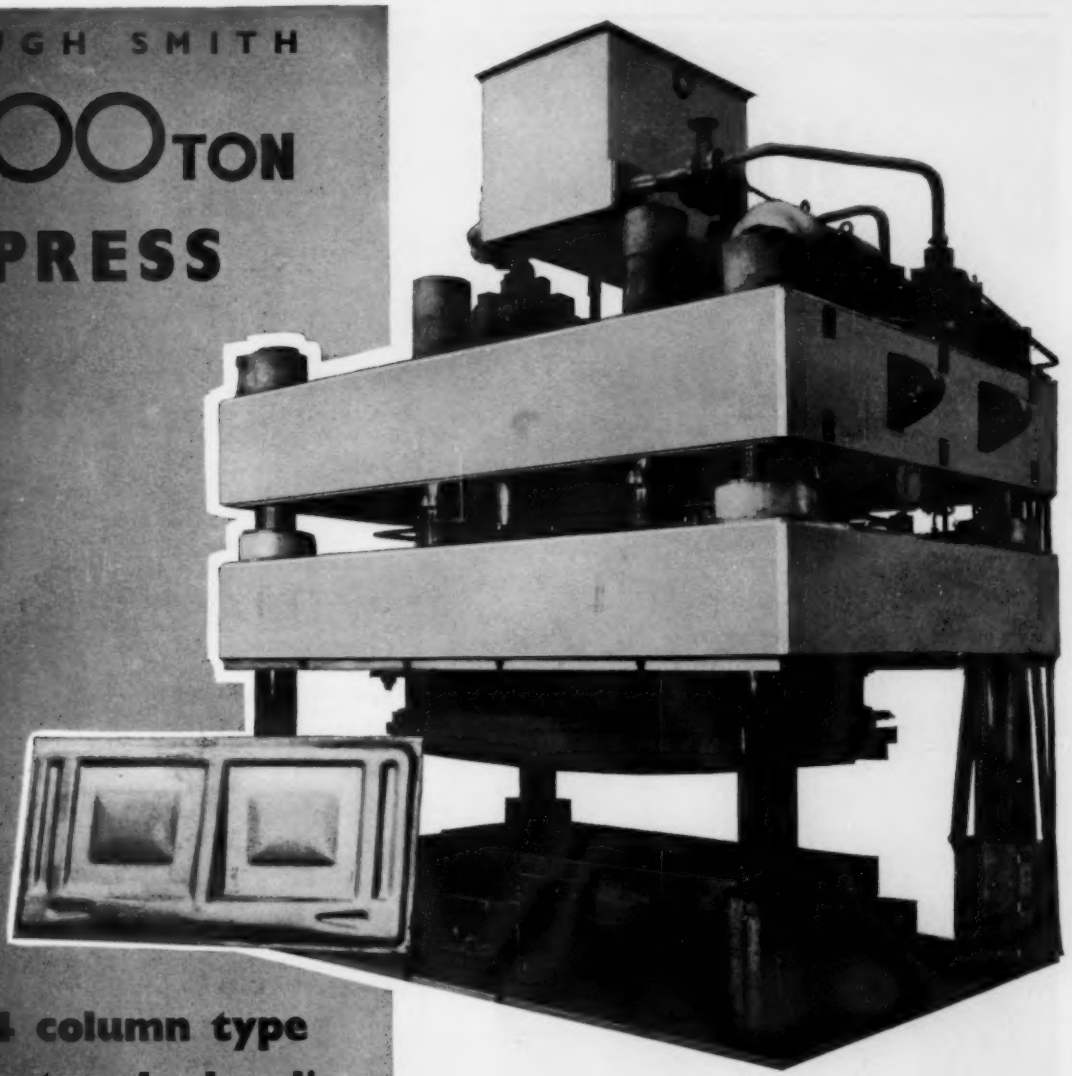

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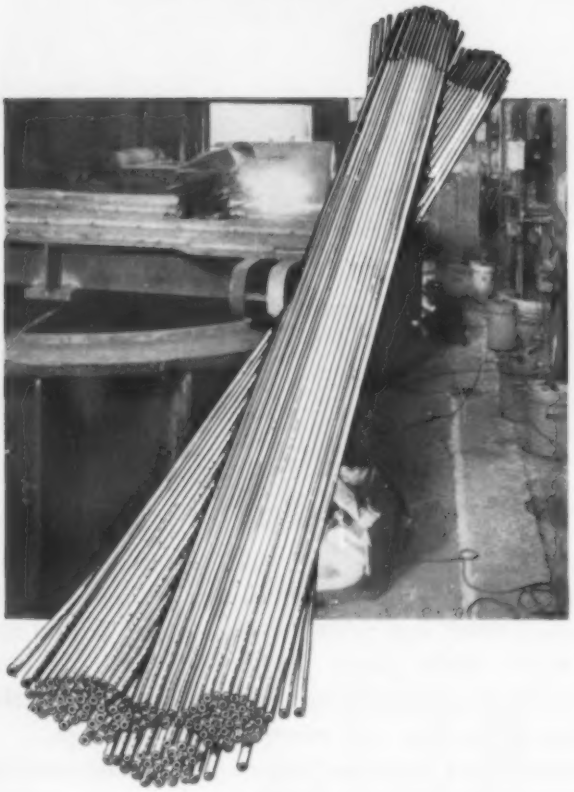

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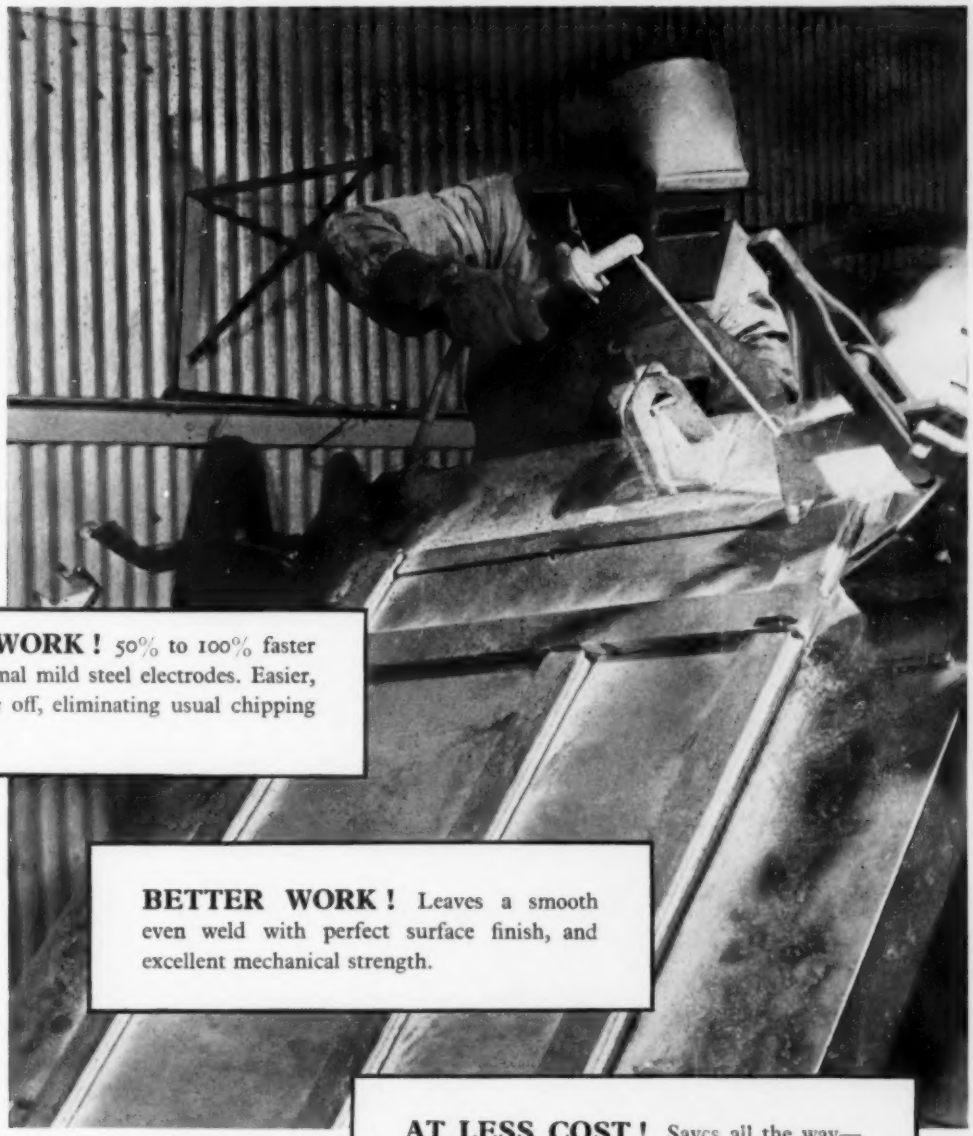

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